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NAVAL POSTGRADUATE SCHOOL  
Monterey, California



THESIS

NUCLEATE POOL BOILING OF HIGH DIELECTRIC  
FLUIDS FROM ENHANCED SURFACES

by

Victor Joseph Lepere Jr.

December 1980

Thesis Advisor:

P. J. Marto

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Nucleate Pool Boiling of High Dielectric  
Fluids from Enhanced Surfaces

by

Victor Joseph Lepere Jr.  
Lieutenant, United States Navy  
B.S., Marquette University, 1974

Submitted in partial fulfillment of the  
requirements for the degree of

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### ABSTRACT

Experimental results of the heat transfer performance of three enhanced heat transfer surfaces, a Union Carbide, Linde High Flux, a Hitachi Thermoexcel-E, a Wieland Gewa-T, and a plain copper surface in the nucleate pool boiling regime in R-113 and FC-72 are presented.

Prior to obtaining the data, each of the surfaces was subjected to one of three initial conditions, and the effect of past history on boiling incipience was observed.

The data showed that all the surfaces behaved in a similar manner prior to the onset of boiling. Temperature overshoots were most pronounced for the initial condition in which the surfaces were submerged in the liquid pool overnight. All of the enhanced surfaces exhibited a two to tenfold increase in the heat transfer coefficient when compared to the plain surface. The High Flux surface was most effective over a broad range of heat fluxes. The Hitachi surface showed a similar gain in heat transfer coefficient to that of the High Flux surface below  $10 \text{ kW/m}^2$ , while the Gewa-T surface was not as effective as the other surfaces at low heat fluxes. At high fluxes, the Gewa-T surface performed in a comparable if not better manner.

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## I. INTRODUCTION

### A. BACKGROUND

Nucleate pool and forced convection boiling from enhanced heat transfer surfaces is being examined in many areas of engineering as a means of attaining high heat fluxes while maintaining low temperature differences between the heated surface and the heat transfer fluid. One area in which these methods of heat transfer have great promise is in the field of electronics cooling. The advent of solid state electronic devices has permitted the miniaturization of electronic components to microscopic sizes. While these order of magnitude reductions in size have many obvious advantages, they create the problem of having to dissipate heat from components of very small size; that is, they create large heat fluxes. Additionally, semiconductor devices are very sensitive to temperature excursions, and as noted by Kraus [1] and Seely and Chu [2], they exhibit either a high failure rate or lower reliability if not adequately cooled. This problem has required the continued use of vacuum tubes or relatively large discrete semiconductor devices for applications requiring high power levels, or operation in poorly ventilated or unventilated spaces.

Since the heat transfer potential of nucleate boiling is well known, this regime was one natural selection for examination as a possible solution to this cooling problem.

As noted by Yilmaz [3], several commercially available heat transfer surfaces have been produced to take advantage of the high heat fluxes attainable in the nucleate boiling regime. These surfaces attempt to increase the heat transfer by greatly increasing the number of nucleation sites on the boiling surface. Nishikawa [4] notes that there are two primary methods used to promote nucleate boiling. The first is to treat the surface in a manner that reduces its wettability, for example, teflon coating sites on a surface. The second, and this seems to be the most promising for a large number of fluids, is to manufacture a surface with re-entrant cavities which trap and hold vapor and keep the nucleation site active.

3M Corporation has commercially produced its "Flourinert" series of high dielectric inert electronics cooling liquids. The combination of these liquids with the surfaces manufactured to promote nucleate boiling offers promise as a means of providing electronics cooling under some very adverse conditions.

Previous investigations of nucleate pool boiling have been made Yilmaz et al [3], and Nishikawa and Ito [4], and Bergles et al [5,6]. Yilmaz et al [3] compared the nucleate pool boiling heat transfer performance of three copper tubes, a Wieland Gewa-T tube, a Hitachi Thermoexcel-E tube, and a Union Carbide, Linde High Flux tube, to a plain copper tube. The experiment was conducted using a horizontal steam heated

tube in p-xylene. Their findings indicated that

for the  $\Delta T$  studied, the High Flux tube performed better than both Thermoexcel-E and Gewa-T tubes, and they in turn performed much better than the plain tube. The Thermoexcel-E tube gave a better performance than Gewa-T at low  $\Delta T$  values, and both performed similarly at high  $\Delta T$  values...

Bergles and Chyu [5] compared the nucleate pool boiling heat transfer characteristics of three copper Union Carbide High Flux test sections to a plain copper tube in distilled water and R-113. The experiments were conducted with three different treatments to the test surface prior to collecting data; subcooling of the test surface, aging the test surface by preboiling it in the pool at  $30,000 \text{ W/m}^2$ , and finally, heating it in air to remove all liquid in the pores. This research indicated:

- (1) The heat transfer coefficients for the porous surfaces were four to ten times higher than for the plain surfaces.
- (2) There was a significant temperature overshoot prior to the initiation of boiling with the High Flux surface in water which was not present with the plain surface. This overshoot was not very sensitive to aging or the power increment changes.
- (3) Both the plain surface and the High Flux surface exhibited temperature overshoot prior to the initiation of boiling in R-113. These overshoots were sensitive to aging, initial subcooling and power increment changes.

Bergles [5] indicated that this temperature overshoot phenomenon and its variance with initial tube treatment and pore size is explainable in terms of the type of nucleation site present, wettability of the surface, and differences in the mechanism of established boiling. He stated that

It is felt that boiling with a High Flux surface involves incipient boiling from doubly re-entrant cavities formed at the surface of the matrix or within the matrix. These cavities retain vapor for considerable subcooling, even with highly wetting liquids; however activation superheat can be high if the active cavities have small mouth radii. Once that boiling is established, there is internal vaporization of liquid films formed on the relatively large surface area and subsequent 'bubbling' of vapor from surface pores ... Other surface pores serve as supply routes for the liquid to the interior.

Bergles [5] also noted that the temperature overshoot and resulting boiling curve hysteresis are potentially serious problems when starting up High Flux boilers with highly wetting liquids. Bergles, Bakhru and Shires [6] conducted nucleate pool boiling studies in water, R-113, and FC-78 using a 304 stainless steel tube, and a 304 stainless steel tube in which photoetched pits were filled with teflon spots. These experiments were conducted using electrically heated tubes in a horizontal orientation. With R-113 and FC-78, the results were basically the same for the plain tube and the tube with teflon pits. As heat fluxes were increased, the heat transfer coefficient followed the convective curve until a high superheat was attained, and then a distinct increase in the heat transfer coefficient was noted as

nucleation occurred. This was followed by an abrupt drop in all temperatures by as much as 27°F. It was also noted that the inception of nucleation could be triggered by vibrating the test surface.

The pool boiling experiments in water showed significantly different results between the plain tube and the tube treated with teflon pits. In order to promote nucleation, superheats of about 10°F were required for the plain tube, while only 2°F of superheat was required for the teflon treated tube.

The conclusions drawn were

that the phenomenon of temperature overshoot hysteresis in ordinary liquids is due to two causes: a) the existence of metastable bubbles which are triggered only at sufficiently high disturbance levels, and b) the deactivation of larger cavities by displacing the vapor by liquid during subcooling. Under conditions of low velocity or pool boiling a) is probably most important; but at high velocity b) should be controlling.

With regard to the teflon treated surface, it was concluded that the teflon pits provided porous non-wetting cavities in water which trapped air and provided nucleation sites that could activate at very low wall temperatures. Additionally, the teflon provided sites for trapping vapor and keeping the site active once boiling had started. This surface was not effective in the R-113 and FC-78 because the teflon was wet by these fluids, and the sites flooded. After flooding occurs, the nucleation sites require a high degree of superheat in order to reactivate.

Nishikawa and Ito [4] conducted experiments involving nucleate pool boiling from horizontal cylinders using R-11,



R-13, and benzene as the cooling fluids. They constructed an enhanced heat transfer surface by sintering copper or bronze spherical particles of 100-1000  $\mu$  in diameter to the outside of a copper tube, thus creating a surface with a large number of re-entrant type cavities to act as nucleation sites. This surface exhibited about a tenfold increase in the heat transfer coefficient for the enhanced tube as compared to a plain tube of the same size. This tenfold increase was for lower heat fluxes about  $2 \times 10^4 \text{ W/m}^2$  with the performance diminishing somewhat at higher heat fluxes.

In summarizing the results of all the previous investigations, the following points are clear:

- 1) There is a four to tenfold increase in the heat transfer coefficient, with a lower  $\Delta T$  ( $T_w - T_s$ ), with the various enhanced surfaces as compared to the plain surfaces in water, R-113, FC 78, R-11, R-13, benzene and p-xylene. The enhanced surfaces are more effective because they provide a large number of nucleation sites from which boiling can occur.
- 2) There are two major methods employed to provide a large number of stable nucleation sites: a) Coat the surface in some manner so that it contains nucleation sites which are non wettable by the heat transfer fluid.  
b) Produce a surface which has a re-entrant type cavity which can trap air or vapor and hold it, thereby providing a stable nucleation site.

- 3) There is a large temperature overshoot prior to the inception of nucleate boiling with the enhanced surfaces in water, R-113, FC 78 and p-xylene. After boiling begins, there is a rapid drop in temperature for the same heat flux.
- 4) The factors which determine if this superheat and resulting hysteresis occur and to what degree, are determined by; cavity size and shape, surface wettability in the fluid of interest, bubble stability, and treatment of the surface prior to boiling (air drying, aging, subcooling).

Since semiconductor devices require operation over a fairly narrow temperature range, it is essential that this hysteretic phenomenon be overcome before nucleate boiling from enhanced surfaces could be employed as a general electronics cooling scheme.

#### B. THESIS OBJECTIVE

The objectives of this thesis are twofold. The first objective is to compare the heat transfer performance of the Hitachi Thermoexcel-E, Union Carbide, Linde High Flux, Wieland Gewa-T and a plain copper tube, in FC-72 a low surface tension, high dielectric liquid, and compare these results with their performance in R-113 under the same conditions.

The second objective is to determine if FC-72 is hysteretic when used in conjunction with these surfaces, and if it is,

to attempt to find a method of pretreating the surface to minimize or prevent this phenomenon.

## II. EXPERIMENTAL DESIGN

### A. FACTORS CONSIDERED

The design of the boiling apparatus was influenced by the requirement to be able to determine the enhanced test section outside wall temperature. It was essential that this should be accomplished in such a way as to minimize the local anomalies in either the boiling surface, or in the heat flow paths in the interior of the test section. Secondly, it was necessary that the fluid in the boiler should be maintained at saturation conditions. Finally, it was essential to minimize the heat transfer through the unenhanced regions at the ends of the test sections. The following parameters were to be determined:

1. Heater sheath wall temperature
2. Test surface outside wall temperature
3. Fluid bulk temperature
4. Vapor temperature
5. Barometric pressure
6. Ambient temperature
7. Power into the test section heater
8. Boiling heat flux from the test surface

### B. DESCRIPTION OF COMPONENTS

Figure 1 is a schematic drawing of the test apparatus and identifies all major components. Figures 2 and 3 are

photographs of the apparatus. Figure 4 is a drawing of the test section while Figure 5 is a drawing of the test section in the boiler.

The apparatus consisted of a cylindrical copper test surface heated on the inside by an electric rod heater with an outside diameter of 12.6 mm. Four thermocouples with an average diameter of 0.76 mm were centered axially on the heater and were soldered in four grooves on the heater surface. These grooves were displaced circumferentially by ninety degrees in order to provide a representation of an average temperature.

One end of the test section was insulated on the inside by a solid teflon plug. The other end, in which the wires protruded from the test section, was insulated with poured epoxy resin. The test section was then attached to an adjustable gas-tight pipe which protruded through the top of the boiler. The boiler vessel consisted of a pyrex glass cylinder with plexiglass cover fitted with a rubber O ring. This vessel was placed on an electric plate heater to allow the liquid to be preboiled for degassing before the run, and to maintain the liquid at saturation temperature throughout the run. The vapor was condensed and returned to the boiler by gravity from a pyrex glass condenser using tap water for cooling.

The following is a description of the test surfaces:

1. Plain tube, Figure 6: A 15.80 mm OD, 15 gauge seamless copper tube.

2. Union Carbide, Linde High Flux, Figure 7: A porous copper matrix of 0.18 mm average thickness brazed to the outside of a 20 gauge copper tube with an overall OD of 18.7 mm. Forty six percent of the copper particles are smaller than 44  $\mu\text{m}$  and the remainder are between 44 and 74  $\mu\text{m}$ .
3. Hitachi Thermoexcel-E, Figure 8: A 16.48 mm OD, and a 13.44 mm ID copper tube with an average pore diameter of 0.13 mm.
4. Wieland Gewa-T, Figure 9: A 740 fins/m copper tube with an ID of 14.48 mm and a 17.91 mm overall OD, a 1.0 mm fin height, and a 0.25 mm gap between fins.

#### C. INSTRUMENTATION

All temperatures were measured with copper-constantan thermocouples. Each thermocouple was read separately through a thermocouple switch and a Newport digital pyrometer which had an accuracy of  $\pm 0.06^\circ\text{C}$ .

The test surface heater voltage was measured by a digital voltmeter accurate to .01 volts. Heater current was determined by measuring the voltage drop across a 2.0236 ohm precision resistor connected in series with the test section heater.

Two thermocouples were placed above the surface of the boiling fluid to determine fluid vapor temperature. One thermocouple was immersed in the fluid pool to monitor fluid bulk temperature.

### III. EXPERIMENTAL PROCEDURE

#### A. PREPARATION OF TEST SECTION

The test sections were fabricated in the following manner:

1. A teflon plug was manufactured to reduce heat transfer longitudinally through the test section. This plug had a machined cavity on its interior end which accepted the heater, and permitted precise positioning of the heater in the enhanced tube.
2. The enhancement was machined off the surface at the ends of the test sections in the regions which were insulated from the heater. This was done in order to maximize heat transfer in the radial direction and minimize longitudinal heat transfer. If longitudinal heat transfer could be reduced to a negligible value, the heat flux calculations could be more accurately and easily ascertained.
3. The heater was centered radially and axially in the test surface, and the void between the heater sheath and the inside tube wall was filled with Eutectic Corporation's 157 Eutectoid solder. This soldering was accomplished under vacuum in order to prevent the formation of insulating air bubbles between the heater sheath and the inside tube wall. Figure 10 is a sketch of the soldering apparatus.

4. The test section was then connected to an L shaped tube by means of a Swagelok fitting. This tube penetrated the boiler vessel cover through a gas tight connection.

#### B. CALIBRATION OF THERMOCOUPLES

Thermocouples were immersed in a Rosemount constant temperature distilled water bath, and were compared with a platinum resistance thermometer as a standard. The temperature was raised from 38°C to 82°C in increments of about five degrees. At each increment, the temperature was allowed to stabilize for five minutes. The thermocouples were read using a Newport digital pyrometer.

#### C. NORMAL OPERATION

At the start of each run, the plate heater was used to vigorously boil the pool for one hour in order to degas the liquid. The plate heater was then used to maintain the pool at saturation temperature. The power to the test section was then increased by controlling the test section heater voltage. The voltage was increased in two to four volt increments until the initiation of boiling occurred, at which point ten volt increments were made until the maximum attainable heat flux was reached. The power was then decreased in the same fashion. At each power setting, the system was permitted to stabilize for five minutes and the following data were recorded: heater voltage, Precision resistor voltage, two thermocouple indications



of saturated vapor temperature, one thermocouple reading of pool temperature, and four thermocouple readings of heater sheath temperature. This procedure was repeated with three pre-boiling treatments to the test surfaces. The first treatment permitted the test surface to cool to ambient temperature immersed in the pool overnight prior to starting a data run. The second procedure was to age the tube by preboiling it at  $30,000 \text{ W/m}^2$  for one hour prior to the run, and the final procedure was to air dry the tube by heating it to  $65^\circ\text{C}$  for ten minutes prior to making a run.

#### D. DATA REDUCTION

Saturation temperature was determined by averaging the calibrated temperature indicated by the two thermocouples placed above the liquid pool.

The test surface wall temperature was assumed to be the temperature of the test cylinder at the base of the surface enhancement. This wall temperature was determined by averaging the readings of the four calibrated thermocouples located inside the test surface with corrections applied for the temperature drops across the wall due to conduction through the solder and the inner portion of the test surface:

$$T_w = T_T - \frac{q \left( \frac{\ln \frac{r_2}{r_1}}{k_1} + \frac{\ln \frac{r_3}{r_2}}{k_2} \right)}{2 \pi L}$$

where:

- $T_w$  = wall temperature at the base of the surface enhancement ( $^{\circ}\text{C}$ )
- $T_T$  = average calibrated thermocouple temperature ( $^{\circ}\text{C}$ )
- $r_1$  = radius of thermocouple locations (m)
- $r_2$  = inside radius of test surface (m)
- $r_3$  = outside radius of test surface to the base of the enhancement (m)
- $k_1$  = thermal conductivity of solder ( $\text{W/m } ^{\circ}\text{C}$ )
- $k_2$  = thermal conductivity of copper ( $\text{W/m } ^{\circ}\text{C}$ )
- $L$  = length of enhanced surface (m)
- $q$  = heat flux ( $\text{W/m}^2$ )

Power to the test section was determined from the following equation:

$$Q = V I$$

where:

- $V$  = cartridge heater input voltage (volts)
- $I$  = cartridge heater input current (amps)

The heat flux was determined from

$$q = Q/A$$

where:

- $A$  = area of test surface at the base of the surface enhancement ( $\text{m}^2$ ).

The heat transfer coefficient was determined from:

$$h = \frac{q}{(T_w - T_s)}$$

where:

$T_w$  = average wall temperature at the base of  
the surface enhancement ( $^{\circ}\text{C}$ )

$T_s$  = average calibrated saturation temperature  
( $^{\circ}\text{C}$ )

$h$  = heat transfer coefficient ( $\text{W}/\text{m}^2 \text{ } ^{\circ}\text{C}$ )

$q$  = heat flux ( $\text{W}/\text{m}^2$ )

#### IV. RESULTS AND DISCUSSION

A total of thirty experimental runs were completed. The runs were grouped on the basis of type of surface (High Flux, Thermoexcel-E, Gewa-T, Plain Copper), working fluid (R-113, FC-72), and prior conditioning of the surface before a run:

- 1) Submerged in the liquid pool overnight at ambient temperature, then submerged in the pool at zero power for one hour while the pool was being vigorously boiled for degassing purposes by the auxiliary heater.
- 2) Aged at  $30 \text{ kW/m}^2$  for one hour in a vigorously boiling pool followed by stabilization at zero power for approximately two minutes.
- 3) Air dried at  $65^\circ\text{C}$  for ten minutes followed by cooling to ambient temperature, the surface was then placed in the pool at zero power for one hour prior to the run while the pool was boiled vigorously with the auxiliary heater for degassing.

Results are compared on the basis of:

- 1) overall heat transfer performance, and
- 2) the degree of superheating experienced prior to the initiation of boiling, hysteresis effects, and the effect of working fluid and prior surface conditioning on boiling incipience.

One run was made for each set of initial conditions described above except for the High Flux surface. Two runs for

each set of conditions were made with this surface in order to demonstrate the reproducibility of the results. In the discussion of the results which follows, each of the figures is not discussed individually. Instead, the salient points are discussed which have been extracted from a comparative study of the figures. The figures are grouped on the basis of similarity of conditions rather than the order in which they are referred to in the text. This arrangement provides a relatively easy means of comparing the results.

On Figure 11, Bergles [5] data for a High Flux surface in R-113 is plotted over the data collected. There is very good agreement between the results of both experiments. On Figure 12, data from the Hitachi Corporation [7] for the Thermoexcel-E surface in R-113 is plotted over the results with fairly good agreement between the two sets of data.

#### A. COMPARISON OF HEAT TRANSFER COEFFICIENT

In R-113 and FC-72, prior to the initiation of nucleate boiling, all of the surfaces behaved in a similar manner. The heat transfer coefficient was somewhat higher than what was predicted by the natural convection correlation for a horizontal cylinder, Figures 13-17. However, the data is in agreement with similar results presented by Bergles [5]. This phenomenon is most likely a result of complex convection currents present in the boiler vessel.

Once boiling was initiated, all three of the enhanced surfaces showed a significant increase in the heat transfer

coefficient as compared to the plain surface. In R-113, the High Flux surface showed an improvement of four to ten times over the heat transfer coefficient of the plain surface, Figures 13 and 16. This is the same as the results reported by Bergles [5]. The greatest improvement is in the region of 8-30 kW/m<sup>2</sup>. The performance of the Thermoexcel-E surface is quite similar to that of the High Flux surface, and is coincident with the High Flux surface for heat fluxes below 20 kW/m<sup>2</sup> once boiling has been initiated, Figures 14 and 15. The Thermoexcel-E surface degrades somewhat in comparison to the High Flux surface above 20 kW/m<sup>2</sup>, but still shows significant improvement over the plain tube until a heat flux near 100 kW/m<sup>2</sup>. The phenomena described above is most likely a result of the number of nucleation sites active on the particular surfaces for a given heat flux. The Gewa-T surface, Figure 17, had about half the heat transfer coefficient of the Thermoexcel-E and High Flux Surfaces below about 20 kW/m<sup>2</sup>. However, this surface improved at higher heat fluxes, and was equal to the performance of the High Flux surface at 100 kW/m<sup>2</sup>. It exceeded the performance of the Thermoexcel-E surface above 70 kW/m<sup>2</sup>. This most likely occurs because the very large cavities created within the Gewa-T surface give it the characteristics of a plain tube with fins, rather than a surface with numerous active sites at low heat fluxes. However, at large heat fluxes, because of the large spacing between the pores, separation of the vapor columns occurs.

As a result, the vapor columns do not coalesce from the large numbers of bubbles being generated at high heat fluxes, and this surface improves relative to the other surfaces.

In FC-72, all of the surfaces showed significant improvement in heat transfer coefficients over the plain tube, Figures 28-32, however the improvement was less than that shown with R-113. The High Flux surface had an overall heat transfer coefficient of two to seven times higher than the plain surface. The Thermoexcel-E surface and the Gewa-T surface had heat transfer coefficients two to five times higher than the plain tube in FC-72. The Thermoexcel-E surface performed slightly better than the Gewa-T surface below  $10 \text{ kW/m}^2$ , while the opposite was true above  $10 \text{ kW/m}^2$ . At about  $200 \text{ kW/m}^2$  all the surfaces except the Gewa-T surface had transitioned to film boiling in FC-72. This most likely occurs because the relatively large spacing between the pores permits separation of the vapor columns and delays the onset of film boiling.

#### B. EFFECTS ON INCIPIENT BOILING

All of the surfaces tested exhibited hysteretic behavior in both R-113, and FC-72. This hysteretic phenomenon was worst in the case where the surface was submerged in the pool overnight. The degree of superheating prior to the initiation of boiling was worse with R-113 than with FC-72. This is most likely due to the different thermal properties of the two fluids.

For all the surfaces tested, initial conditioning of the surface by air drying and aging resulted in a significant reduction of the degree of superheating required in order to initiate boiling. This was probably due to the fact that when the surface sits submerged in the pool overnight, all but the smaller nucleation sites become flooded, requiring high superheats to generate vapor and activate the flooded sites. In the cases where the surfaces were either aged or air dried prior to the run, either air or vapor was already trapped in the nucleation sites, and a lower heat flux and superheat were required to initiate boiling. It is worthwhile noting that due to the high wettability of both R-113 and FC-72, it does not require much time to flood and deactivate a nucleation site. In one of the runs with the High Flux surface in R-113 with initial aging, the surface was permitted to sit submerged in the pool for about thirty minutes after boiling had ceased upon completion of the aging process. As seen in Figure 18, a heat flux of about  $1500 \text{ W/m}^2$  was required to initiate boiling. By comparison, Figures 13 and 14 show that this is not as bad as the  $2\text{-}4 \text{ kW/m}^2$  required to activate the surface when it was initially submerged overnight, but it is significantly higher than the  $200 \text{ W/m}^2$  required to initiate boiling when the surface is aged without any subsequent subcooling, as evident in Figure 19.

Figures 34 and 38 show that the High Flux surface was non hysteretic in FC-72 with initial aging or air drying. Figures 19 and 24 show that there was a minimal hysteresis



with the High Flux surface in R-113 with initial air drying or aging.

From Figures 40 and 35 we can see that the Thermoexcel-E surface exhibited minimal hysteresis in FC-72 with initial air drying, and with initial aging. Figures 20 and 25 show that in R-113 the Thermoexcel-E surface exhibited minimal hysteresis with both initial aging, and initial air drying.

As seen in Figure 26 the plain copper surface was almost non hysteretic in R-113 with initial air drying, and Figure 36 shows that it exhibited minimal hysteresis in FC-72 with initial aging.

Figures 37 and 22 indicate that the Gewa-T surface was practically nonhysteretic in FC-72 and R-113 with initial aging.

Of all the surfaces tested, the High Flux surface experienced the most rapid and dramatic activation after being submerged in the pool overnight. Once boiling initiated, the entire test section was active in about .015 seconds in both R-113 and FC-72. Figures 43-46 are sequential movie frames of the initiation of boiling on the High Flux surface in R-113 after being submerged in the pool for three hours. The filming was done at 64 frames per second. In Figure 43, no boiling is evident. In the following frame, Figure 44, the initiation of boiling is seen in the lower left half of the surface. In the following two frames, Figures 45 and 46, the entire surface is active. This rapid initiation of boiling across the surface is probably due to the interconnecting

character of the surface. Once one site activates, the rapid diffusion and expansion of the vapor through the matrix activates additional nucleation sites. The other surfaces all activated gradually with increasing heat flux. With both the Gewa-T and the Thermoexcel-E surfaces, a few sites first became active at some incipient heat flux. As the heat flux increased beyond this value, additional sites became active. These initial sites subsequently activated an entire interconnecting ring around the cylinder.

## V. CONCLUSIONS

1) By increasing the number of nucleation sites, the enhanced surfaces show a two to tenfold increase in the heat transfer coefficient when compared to the plain copper tube.

2) The High Flux surface offers the greatest overall heat transfer coefficient of all the surfaces tested over a broad range of heat fluxes. This is probably due to the very high density of nucleation sites and the interconnected nature of these sites as compared to the machined surfaces.

3) The degree of superheat required to activate the various surfaces is sensitive to initial surface conditioning and fluid properties.

4) For the case where the tube was submerged in the pool overnight, the High Flux surface exhibited a very abrupt transition to boiling. Once boiling initiates, all the nucleation sites are activated almost simultaneously. When there is no initial subcooling or flooding of the nucleation sites, the High Flux surface behaves in a less violent manner, although there is still a fairly rapid activation of the entire surface once boiling is initiated.

5) The enhanced heat transfer surfaces tested exhibited non hysteretic behavior in the heat flux range of about 10-100  $\text{kW/m}^2$  in both R-113 and FC-72.

6) All the surfaces, except the Gewa-T surface, displayed a critical heat flux of about 200  $\text{kW/m}^2$  in FC-72. The critical

heat flux for all these surfaces in R-113 could not be determined since it was above the maximum heat flux attainable with this apparatus.

## VI. RECOMMENDATIONS

It is recommended that:

(1) This study be continued using different dielectric liquids with the same surfaces in an attempt to find a fluid which is non wetting to the different surfaces.

(2) The same fluids be used in conjunction with the various surfaces using different pore sizes, in an attempt to find an optimum surface with these fluids.

(3) A surface similar to the High Flux surface be constructed containing sacrificial anodes capable of generating gas within the surface which would promote the initiation of boiling at lower superheats.

(4) The effect of ultrasonic waves on boiling incipience with these surfaces be examined.

(5) A study be conducted using a hybrid Gewa-T surface with sintered particles inside the cavities.

(6) A study be conducted of the effect of the number of fins per meter on the transition to film boiling with the Gewa-T surface.

(7) The ends of the test sections be constructed of stainless steel to minimize the heat losses through the ends when operating in the natural convection regime.

APPENDIX A  
FLUID PROPERTIES

1. FLOURINERT FC-72 [8]

Boiling Point, 1atm	56°C
Density, 25°C	1.9 g/cm <sup>3</sup>
Specific Heat, 25°C	0.25 cal/g °C
Heat of Vaporization at Boiling Point	21 cal/g
Thermal Conductivity, 25°C	0.057 W/m °C
Surface Tension, 25°C	12 dynes/cm
Dielectric Constant, 25°C (1 kHz)	1.76
Average Molecular Weight	340

2. R-113 [9]

Boiling Point, 1atm	47.57°C
Density, 25°C	1.565 g/cm <sup>3</sup>
Specific Heat	0.218 cal/g (°C)
Heat of Vaporization at Boiling Point	35.07 cal/g
Thermal Conductivity, 25°C	0.065 W/m °C
Surface Tension, 25°C	23 dynes/cm
Dielectric Constant, 25°C	2.41
Molecular Weight	187

APPENDIX B  
UNCERTAINTY ANALYSIS

(a) UNCERTAINTY IN AREA

$$\omega_D = \omega_L = \pm 0.010 \text{ inch} \quad \text{Due primarily to non uniform cylinder diameter}$$

$$A = \pi D L$$

where:

D = Cylinder diameter to base of enhancement

L = Length of enhanced surface

$$\frac{\partial A}{\partial D} = \pi L$$

$$\frac{\partial A}{\partial L} = \pi D$$

Therefore,

$$\omega_A = [(\pi L \omega_D)^2 + (\pi D \omega_L)^2]^{1/2}$$

$$\frac{\omega_A}{A} = [(\frac{\omega_D}{D})^2 + (\frac{\omega_L}{L})^2]^{1/2}$$

$$= [(\frac{0.010}{D})^2 + (\frac{0.010}{L})^2]^{1/2}$$

<u>Surface</u>	<u>d</u>	<u><math>\frac{\omega_A}{A}</math></u>
Hitachi Thermoexcel E	0.635	0.022 or 2.2%
Linde High Flux	0.729	0.019 or 1.9%

<u>Surface</u>	<u>d</u>	<u><math>\frac{\omega_A}{A}</math></u>
Gewa-T	0.625	0.023 or 2.3%
Plain Tube	0.622	0.023 or 2.3%

(b) UNCERTAINTY IN POWER

$$\omega_I = \pm 0.005 \text{ A at low power levels}$$

$$\omega_I = \pm 0.05 \text{ A at high power levels}$$

$$\omega_V = \pm 0.05 \text{ V at low power levels}$$

$$\omega_V = \pm 0.5 \text{ V at high power levels}$$

The difference in the uncertainties at high and low power levels is due to larger fluctuations in source voltage and current at higher power levels.

$$Q = V I$$

$$\frac{\partial Q}{\partial V} = I$$

$$\frac{\partial Q}{\partial I} = V$$

$$\omega_Q = [(I\omega_V)^2 + (V\omega_I)^2]^{1/2}$$

$$\frac{\omega_Q}{Q} = [(\frac{\omega_V}{V})^2 + (\frac{\omega_I}{I})^2]^{1/2}$$

$$= [(\frac{.05}{2.034})^2 + (\frac{.005}{.070})^2]^{1/2}$$

$$= 0.076 \text{ or } 7.6\% \text{ at the lowest power level where heater voltage of 2.034 volts and heater current of 0.70 amps were the lowest used in any run}$$



$$\frac{\omega_Q}{Q} = [(\frac{.50}{121.3})^2 + (\frac{.05}{4.20})^2]^{1/2}$$

= .013 or 1.3% at the highest power level where  
121.3 volts and 4.20 amps were the highest  
used in any run

(c) UNCERTAINTY IN HEAT FLUX

$$q = \frac{Q}{A}$$

$$\frac{\partial q}{\partial Q} = \frac{1}{A}$$

$$\frac{\partial q}{\partial A} = -\frac{Q}{A^2}$$

$$\omega_q = [(-\frac{Q}{A^2} \omega_A)^2 + (\frac{1}{A} \omega_Q)^2]^{1/2}$$

$$\omega_A = [(\pi L \omega_D)^2 + (\pi D \omega_L)^2]^{1/2}$$

$$\omega_Q = [(I \omega_V)^2 + (V \omega_I)^2]^{1/2}$$

$$\frac{\omega_q}{q} = [(\frac{\omega_A}{A})^2 + (\frac{\omega_Q}{Q})^2]^{1/2}$$

$$= [(\frac{\omega_D}{D})^2 + (\frac{\omega_L}{L})^2 + (\frac{\omega_V}{V})^2 + (\frac{\omega_I}{I})^2]^{1/2}$$

Surface

$$\frac{\omega_q}{q}$$

Hitachi Thermoexcel E

.058 or 5.8% lowest power level

.021 or 2.1% highest power level

$$\frac{\omega_Q}{Q} = [(\frac{.50}{121.3})^2 + (\frac{.05}{4.20})^2]^{1/2}$$

= .013 or 1.3% at the highest power level where  
121.3 volts and 4.20 amps were the highest  
used in any run

(c) UNCERTAINTY IN HEAT FLUX

$$q = \frac{Q}{A}$$

$$\frac{\partial q}{\partial Q} = \frac{1}{A}$$

$$\frac{\partial q}{\partial A} = -\frac{Q}{A^2}$$

$$\omega_q = [(-\frac{Q}{A^2} \omega_A)^2 + (\frac{1}{A} \omega_Q)^2]^{1/2}$$

$$\omega_A = [(\pi L \omega_D)^2 + (\pi D \omega_L)^2]^{1/2}$$

$$\omega_Q = [(I \omega_V)^2 + (V \omega_I)^2]^{1/2}$$

$$\frac{\omega_q}{q} = [(\frac{\omega_A}{A})^2 + (\frac{\omega_Q}{Q})^2]^{1/2}$$

$$= [(\frac{\omega_D}{D})^2 + (\frac{\omega_L}{L})^2 + (\frac{\omega_V}{V})^2 + (\frac{\omega_I}{I})^2]^{1/2}$$

Surface

$$\frac{\omega_q}{q}$$

Hitachi Thermoexcel E

.058 or 5.8% lowest power level

.021 or 2.1% highest power level

<u>Surface</u>	<u><math>\frac{wg}{q}</math></u>
Linde High Flux	.077 or 7.7% lowest power level
	.019 or 1.9% highest power level
Gewa-T	.053 or 5.3% lowest power level
	.021 or 2.1% highest power level
Plain tube	.055 or 5.5% lowest power level
	.022 or 2.2% highest power level

This analysis excludes losses from the unenhanced ends of the test surfaces. With the exception of the plain copper tube, these losses are within the bounds of the uncertainties above once boiling initiates. The losses are significantly larger prior to the initiation of boiling. Appendix C shows the effect of end losses at different power levels.

(d) UNCERTAINTY IN  $\Delta T$

0.05°C at lowest power level

0.50°C at highest power level

0.05°C at lowest power level

0.10°C at highest power level

These uncertainties include the effects of fluctuations in the Newport pyrometer readings, uncertainty in the location of the thermocouples and solder thickness around the heater, and the use of an average temperature reading for the four thermocouples in the test section.

$$\Delta T = T_w - T_s$$

$$\frac{\partial \Delta T}{\partial T_w} = 1$$

$$\frac{\partial \Delta T}{\partial T_s} = -1$$

$$\omega_{\Delta T} = [(\frac{\partial \Delta T}{\partial T_w} \omega_{T_w})^2 + (\frac{\partial \Delta T}{\partial T_s} \omega_{T_s})^2]^{1/2}$$

$$= 0.071^\circ\text{C at lowest power level}$$

$$= 0.510^\circ\text{C at highest power level.}$$

Therefore,

$$\frac{\omega_{\Delta T}}{\Delta T} = \frac{.071}{0.3} = .237 \text{ or } 23.7\% \text{ at low } \Delta T$$

$$\frac{\omega_{\Delta T}}{\Delta T} = \frac{0.510}{38.5} = .013 \text{ or } 1.3\% \text{ at high } \Delta T$$

$$\frac{\omega_{\Delta T}}{\Delta T} < .10 \text{ or } 10\% \text{ for } \Delta T > 0.71 \text{ or approximately } 95\% \text{ of the data collected.}$$

(e) UNCERTAINTY IN HEAT TRANSFER COEFFICIENT

$$h = q/\Delta T$$

$$\frac{\partial h}{\partial q} = \frac{1}{\Delta T}$$

$$\frac{\partial h}{\partial \Delta T} = - \frac{q}{\Delta T^2}$$

$$\omega_h = \left[ \left( \frac{1}{\Delta T} \omega_q \right)^2 + \left( - \frac{q}{\Delta T^2} \omega_{\Delta T} \right)^2 \right]^{1/2}$$

$$\frac{\omega_h}{h} = \left[ \left( \frac{\omega_q}{q} \right)^2 + \left( \frac{\omega_{\Delta T}}{\Delta T} \right)^2 \right]^{1/2}$$

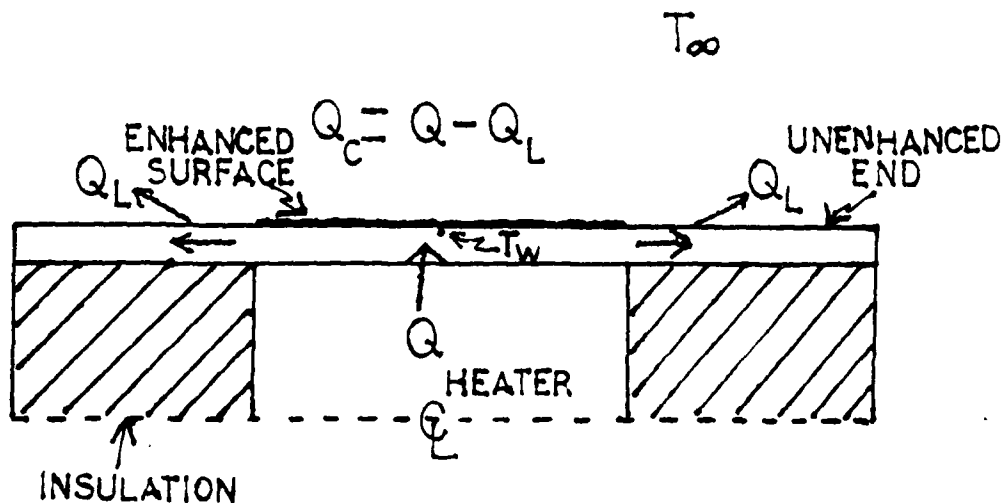
<u>Surface</u>	$\omega_h \left[ \frac{\text{Watts}}{\text{m}^2 \text{ } ^\circ\text{C}} \right]$	$\frac{\omega_h}{h}$
Hitachi Thermo-excel E	20.36	0.117 or 11.7% lowest power level
	300.7	0.032 or 3.2% highest power level
Linde High Flux	3.18	0.066 or 6.6% lowest power level
	1221.8	0.044 or 4.4% highest power level
Gewa-T	3.96	0.062 or 6.2% lowest power level
	1014.9	0.053 or 5.3% highest power level
Plain tube	11.72	0.090 or 9% lowest power level
	211.6	0.0011 or 0.11% highest power level

## APPENDIX C

### TEST SECTION LOSSES FROM THE UNENHANCED ENDS

Sample Calculation for the Thermoexcel-E Surface  
in R-113

The assumption is made that the unenhanced end sections of the test surface act as fins with insulated ends. To determine the temperature gradient along the fin we start with the assumption that the temperature at the base of the fin is the same as the average wall temperature of the test section.  $T_{\infty}$  is assumed to be the pool bulk temperature. The fluid properties of the working fluid are evaluated at the film temperature,  $T_f$ . We assume that along the fins we have the case of free convection from a horizontal cylinder. The figure below is a schematic cross sectional drawing of the system.



Consider the case where:

$$Q = 14.16 \text{ watts}$$

$$T_{\infty} = 120.5 \text{ }^{\circ}\text{F}$$

$$T_w = 138.6 \text{ }^{\circ}\text{F, and}$$

$$T_f = \frac{120.5 + 138.6}{2} = 129.6 \text{ }^{\circ}\text{F}$$

The Prandtl Number is given by

$$\text{Pr} = \frac{\mu c_p}{k}$$

where:

$$\mu = \text{viscosity lbm/ft hr}$$

$$k = \text{liquid thermal conductivity BTU/hr ft }^{\circ}\text{F}$$

$$c_p = \text{specific heat BTU/lbm }^{\circ}\text{F.}$$

If the properties of R-113 are evaluated at the film temperature,  $T_f$ , we get:

$$\text{Pr} = \frac{\mu c_p}{k} = \frac{(1.18)(0.236)}{.0400} = 6.96.$$

The Grashof Number is:

$$\text{Gr} = \frac{g \beta \Delta T D^3}{\nu^2}$$

where:

$$\beta = \text{volume coefficient of expansion }^{\circ}\text{F}^{-1}$$

$$\Delta T = T_w - T_{\infty} \text{ }^{\circ}\text{F}$$

$T_w$  = average tube wall temperature °F

$T_\infty$  = fluid bulk temperature °F

$D$  = tube diameter ft, and

$\nu$  = kinematic viscosity  $\text{ft}^2/\text{hr}$

$$\begin{aligned} Gr &= \frac{(32.2)(.00093)(138.6 - 120.5)(.054)^3(3600)^2}{(0.0128)^2} \\ &= 6.75 \times 10^6 \end{aligned}$$

The Rayleigh Number is then:

$$Ra = Gr Pr = (6.75 \times 10^6)(6.96) = 4.7 \times 10^7$$

For Rayleigh numbers between  $10^4$  and  $10^9$ , Holman [10] gives the following correlation:

$$Nu = 0.53(Ra)^{1/4}$$

Using the Rayleigh Number from above gives

$$Nu = 0.53(4.7 \times 10^7)^{1/4} = 43.88$$

The heat transfer coefficient is then calculated:

$$h = \frac{Nu k}{D} = \frac{(43.88)(.040)}{.054} = 32.5 \text{ BTU/hr ft}^2 \text{ °F}$$

Assuming that the ends of the test surface act as fins with insulated ends, we can use the following equation from Holman [11] to determine the heat loss,  $Q_L$ , from the ends of the test section.



$$Q_L = [h P k A]^{1/2} \theta_o \tanh mL$$

where:

$h$  = heat transfer coefficient

$P$  = tube outside wall perimeter ft

$k$  = thermal conductivity of copper BTU/hr ft °F

$A$  = tube cross sectional area ft<sup>2</sup>

$$m = \left[ \frac{h P}{k A} \right]^{1/2} \text{ ft}^{-1}$$

$L$  = fin length ft, and

$$\theta_o = T_w - T_\infty \text{ °F}$$

The following corrections are applied to the heat loss equation above. The Harper Brown correction is applied to the fin length to determine a corrected fin length,  $L_c$ , to compensate for the thickness of the fin so that

$$L_c = L + t/2 \text{ ft}$$

$$= 0.104 + .008/2 = .108 \text{ ft}$$

$t$  = fin thickness.

$$m = \left[ \frac{h P}{k A} \right]^{1/2}$$

$$P = \pi D = \pi (.054) = .170 \text{ ft}$$

$$A = \frac{\pi}{4}[(D_o)^2 - (D_i)^2] = \frac{\pi}{4}[ (.054)^2 - (.044)^2 ]$$

$$= 0.00076 \text{ ft}^2$$

Therefore,

$$m = \left[ \frac{(32.5)(.170)}{(221.3)(.00076)} \right]^{1/2} = 5.73 \text{ ft}^{-1}$$

$$m L_c = (5.73)(.108) = .618$$

$$\tanh m L_c = \tanh .618 = 0.549, \text{ and finally,}$$

$$Q_L = [h P k A]^{1/2} \theta_o \tanh m L_c$$

$$= [(32.5)(.170)(221.3)(.00076)]^{1/2} (18.1)(.549)$$

$$= 9.57 \frac{\text{BTU}}{\text{hr}} \text{ or } 2.81 \text{ Watts.}$$

This value could be corrected slightly by iterating on the fin temperature difference to calculate a new heat transfer coefficient. Since heat is lost through both ends, a total of 5.62 Watts are lost through the ends of the tube.

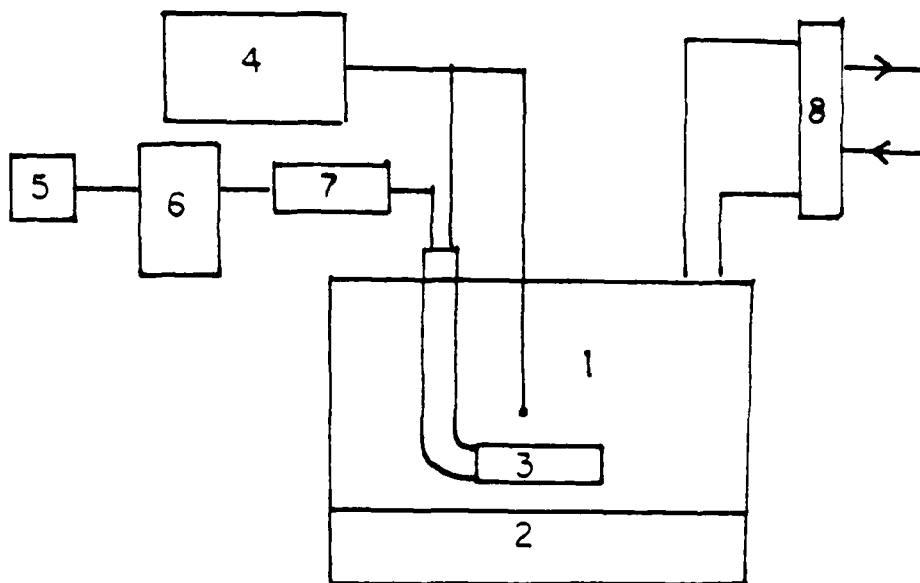
$$\frac{Q_L}{Q} = \frac{5.62}{14.16} = .397$$

Almost forty percent of the heat is lost through the ends of the test section when the total heat in is 14.16 watts.

For all the test sections the losses through the tube ends are a significant factor prior to the initiation of

boiling, but are within the bounds of the experimental uncertainty for the enhanced surfaces once boiling initiates. The table below shows the magnitude of the heat loss through the ends of the cylinders at different power levels. The  $\uparrow$  symbol indicates that the data was taken during an increasing power excursion. The  $\downarrow$  symbol indicates data taken while decreasing power from the maximum value.

Surface	Q (Watts)	$Q_L/Q$	$\omega_Q/Q$
Thermoexcel-E	14.2 $\uparrow$	.397	.058
	72 incipience	.012	.058
	256.2	.018	.021
	7.18 $\downarrow$	0	.058
High Flux	3.24 $\uparrow$	.273	.077
	12.9 incipience	.01	.077
	285.7	.006	.019
	3.6 $\downarrow$	.011	.077
Gewa-T	10.92 $\uparrow$	.245	.053
	44.28	.0002	.053
	286.5	.011	.021
	4.6 $\downarrow$	.008	.053
Plain Surface	3.93 $\uparrow$	.211	.055
	14.8 $\downarrow$	.14	.055
	293.0	.028	.022



Key:

1. Test Vessel
2. Auxiliary heater
3. Test section
4. Digital pyrometer
5. 115 Volt AC power source
6. Variac
7. Digital voltmeter
8. Condenser

Figure 1. Schematic of Test Apparatus

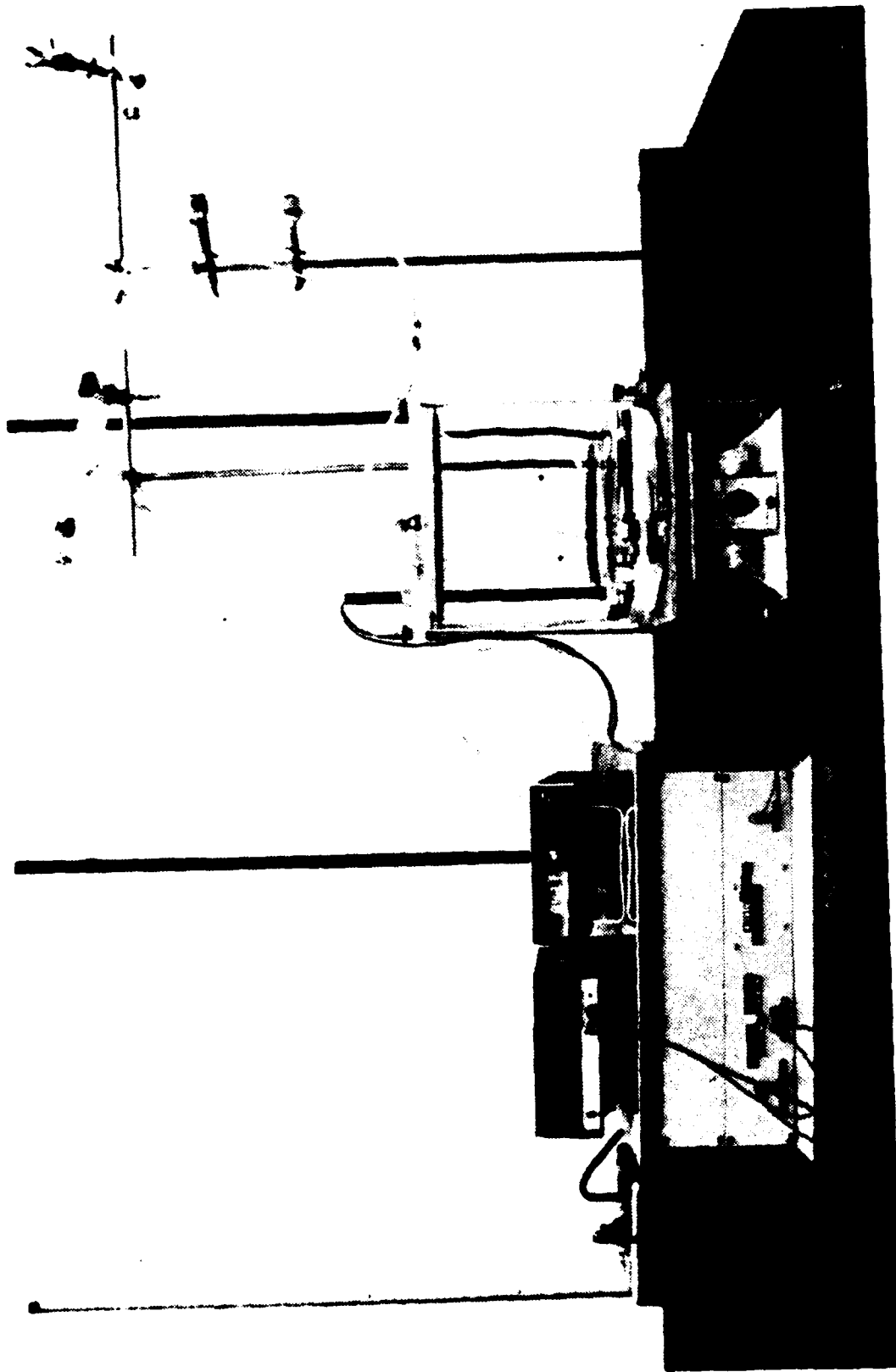


Figure 2. Photograph of Experimental Apparatus

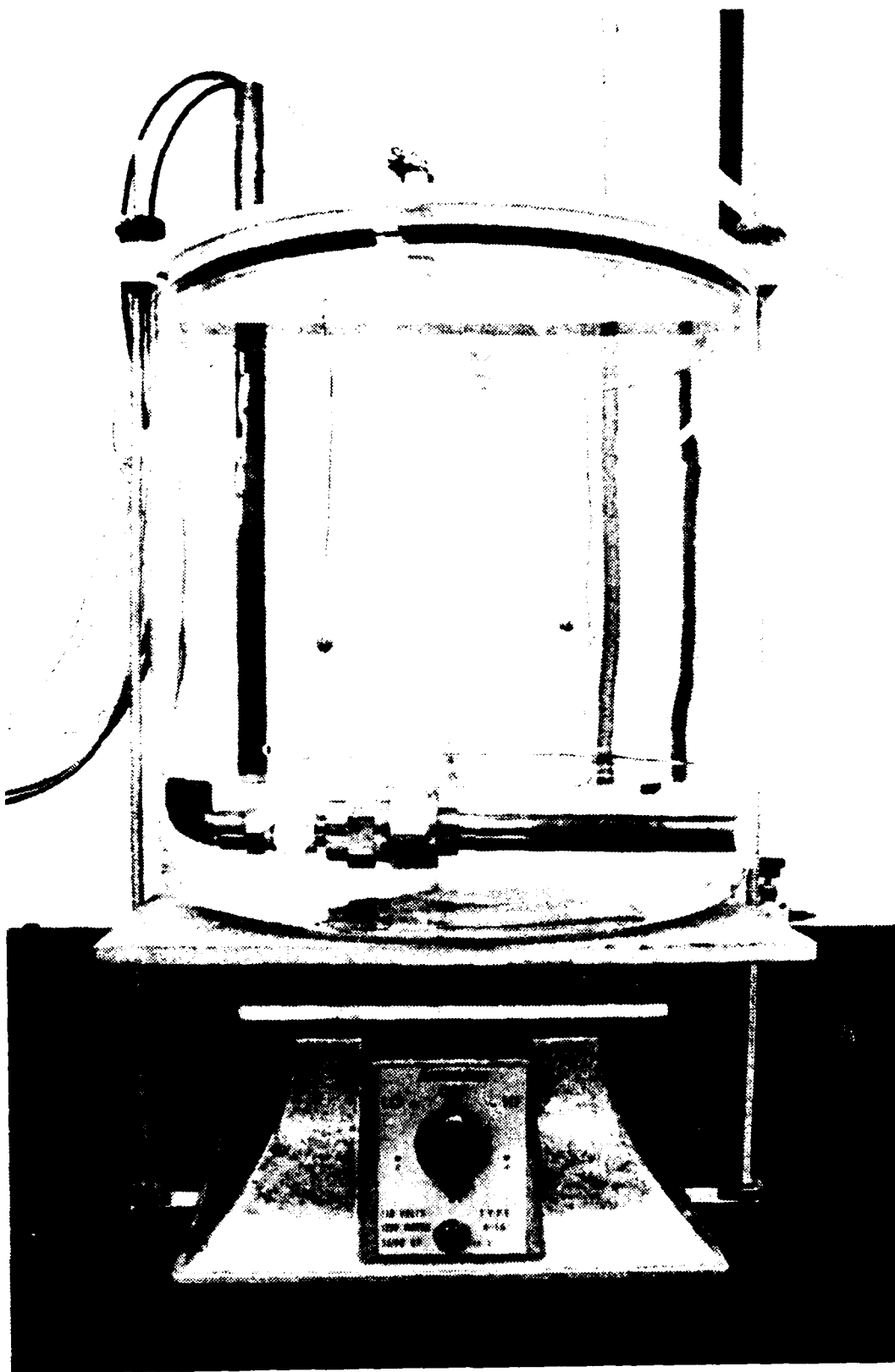


Figure 3. Photograph of Test Section in Boiler

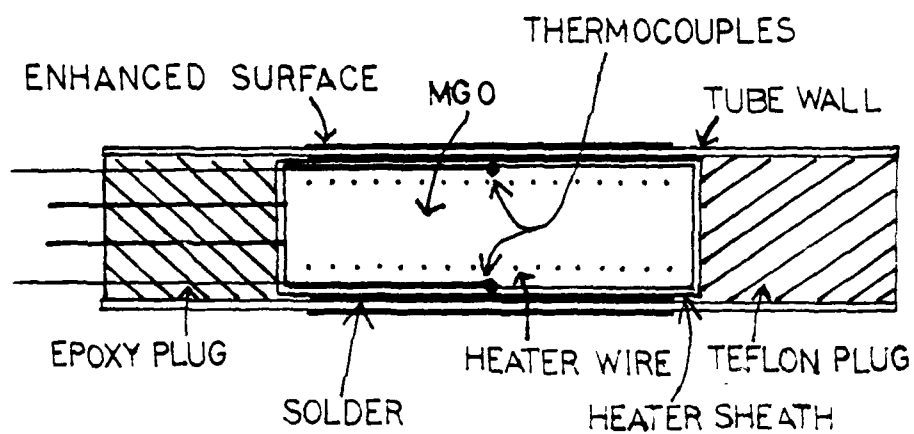


Figure 4. Cross Sectional Drawing of Test Section

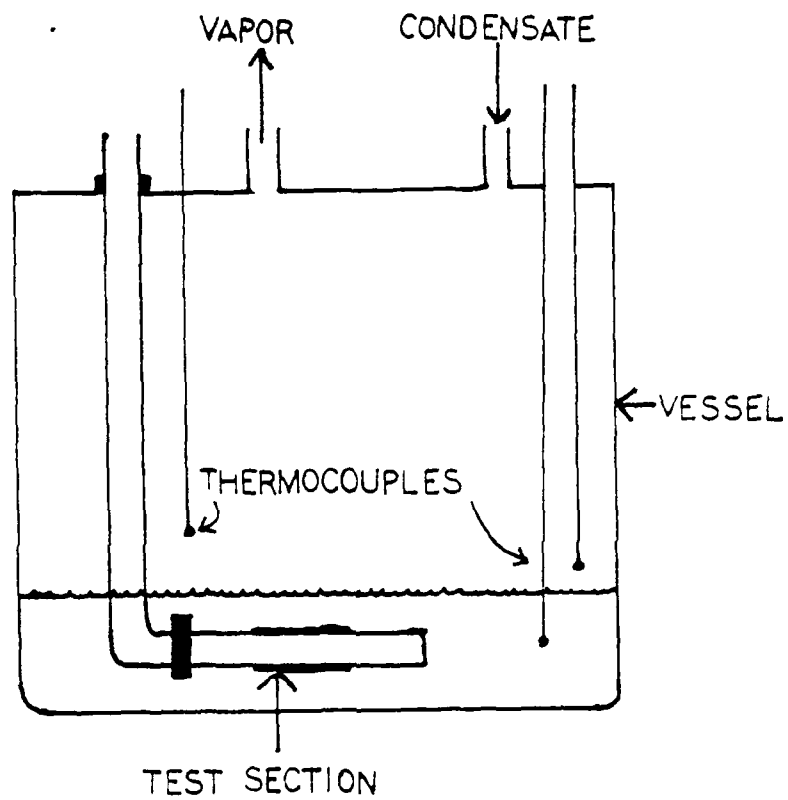


Figure 5. Schematic Drawing of Test Section in Boiler



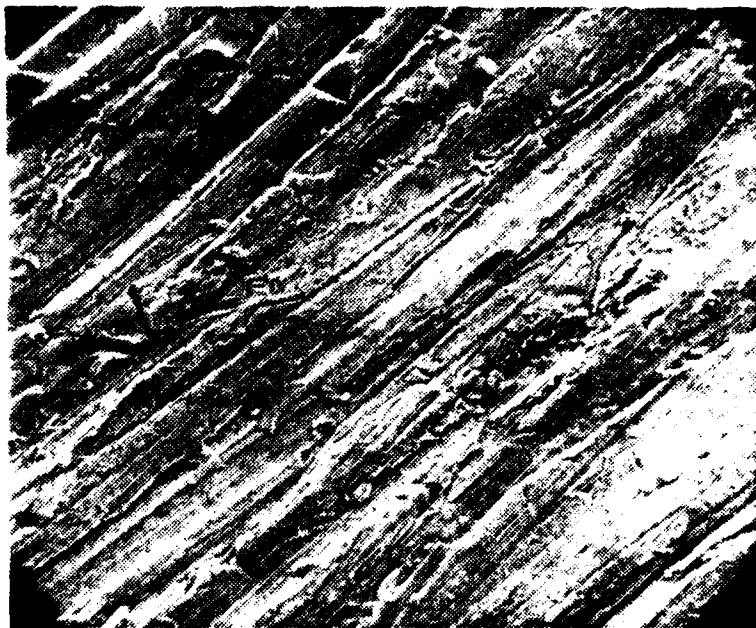


Figure 6. Scanning Electron Micrograph of Plain Copper Surface 500X

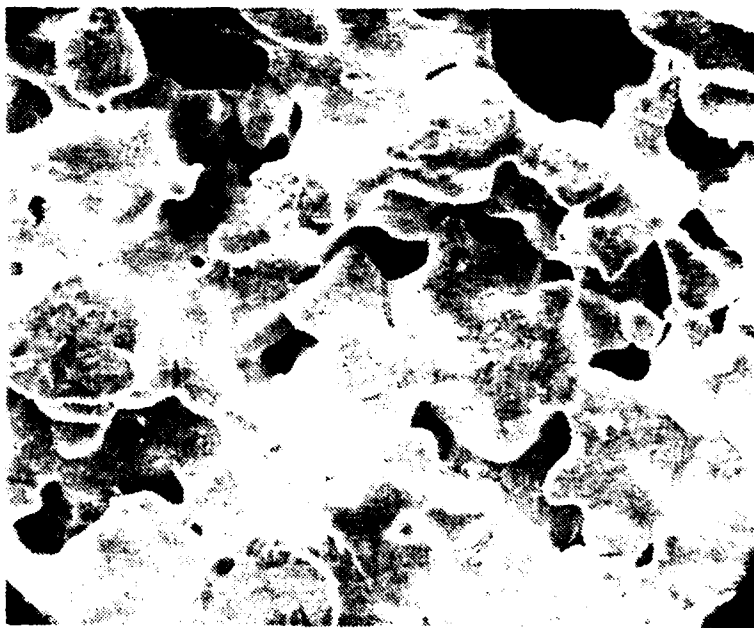


Figure 7. Scanning Electron Micrograph of  
High Flux Surface 500X

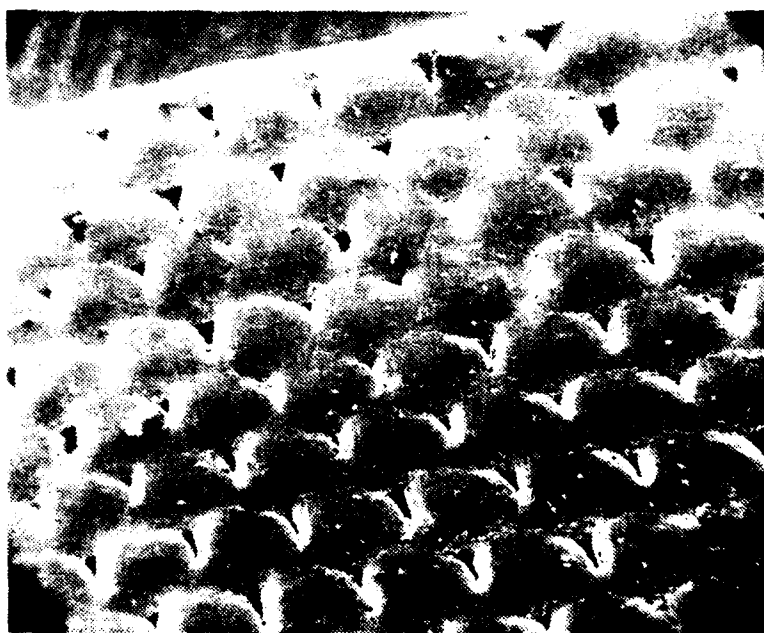


Figure 8. Scanning Electron Micrograph of  
Thermoexcel-E Surface 20X



Figure 9. Scanning Electron Micrograph of Cross  
Section of Gewa-T Surface 20X

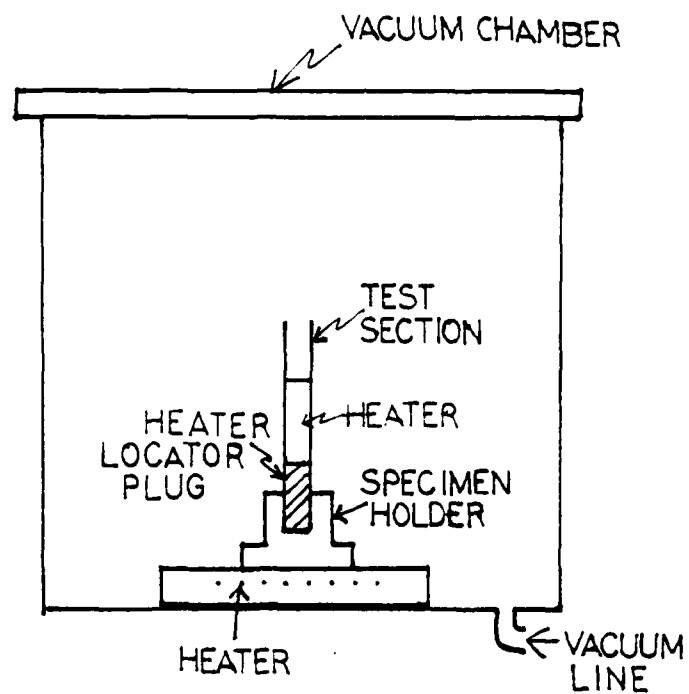


Figure 10. Sketch of Soldering Apparatus Used in Preparation of Test Surfaces

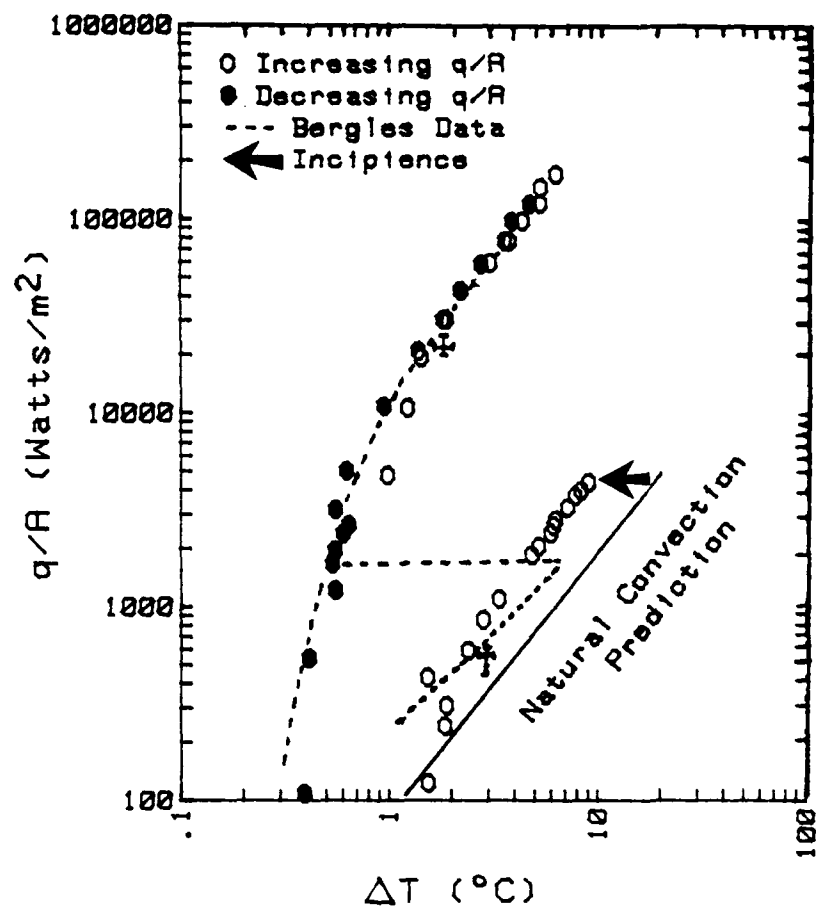


Figure 11. High Flux Surface in R-113--Submerged in Pool Overnight with Bergles Data Imposed

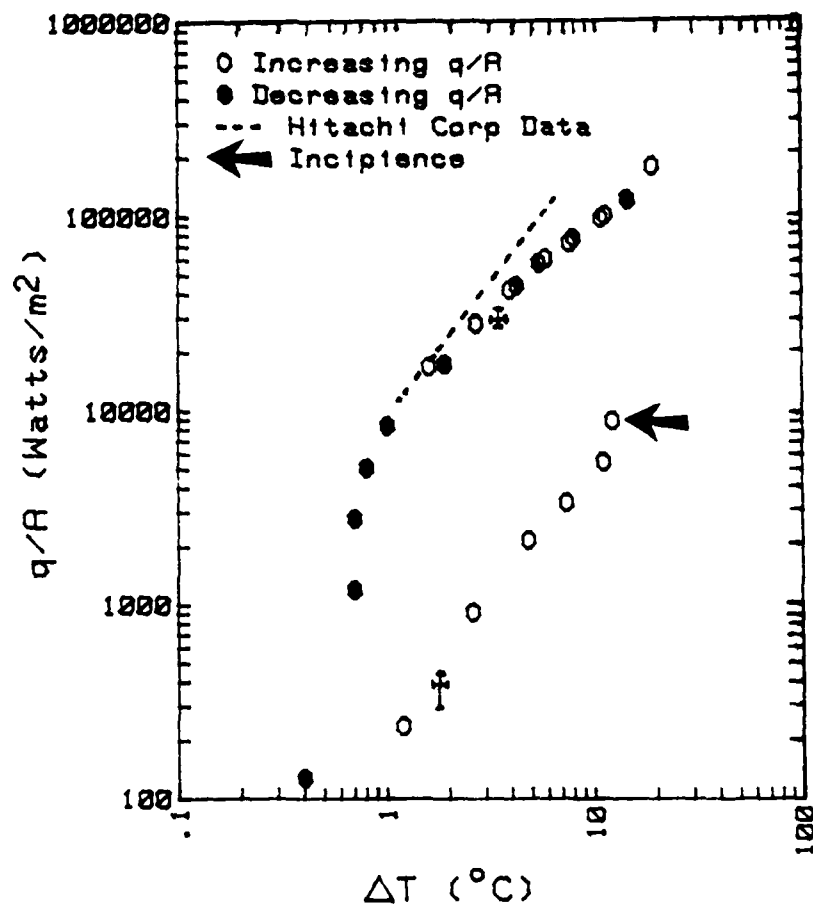


Figure 12. Thermoexcel-E in R-113--Submerged in Pool Overnight with Hitachi Corporation Data Imposed

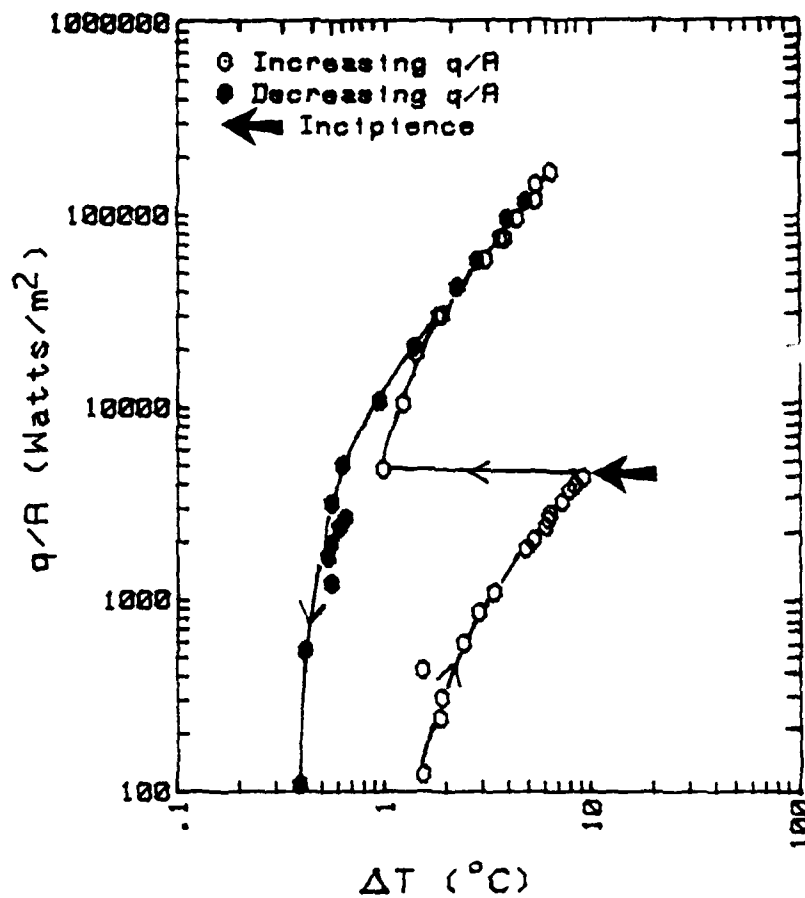


Figure 13. High Flux Surface in R-113--Submerged in Pool Overnight



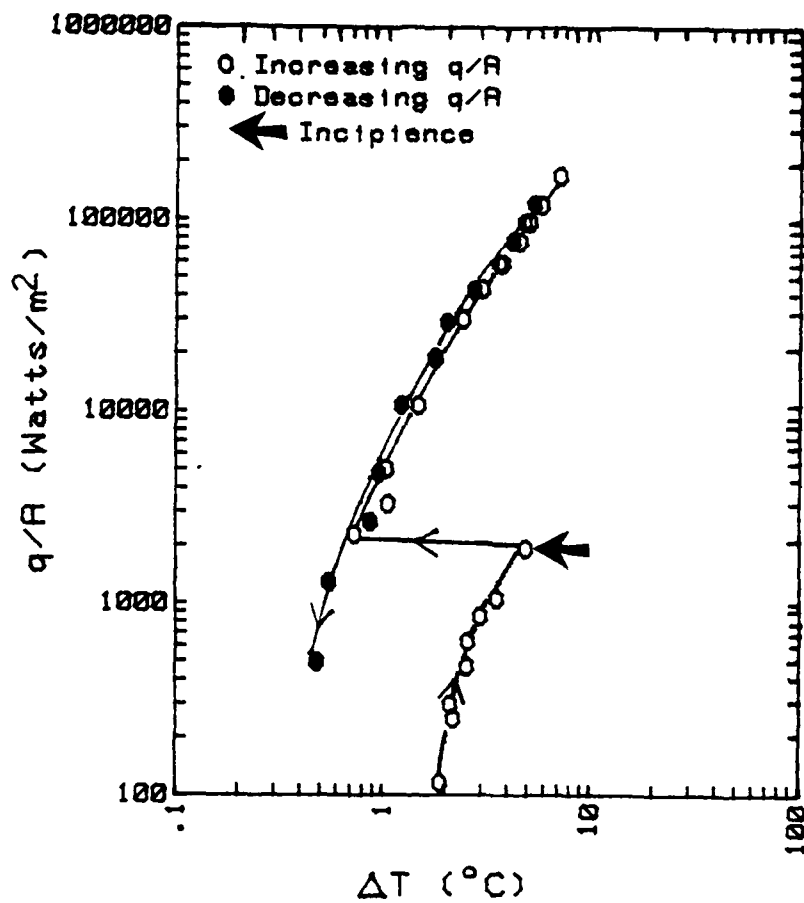


Figure 14. High Flux Surface in R-113--Submerged in Pool Overnight

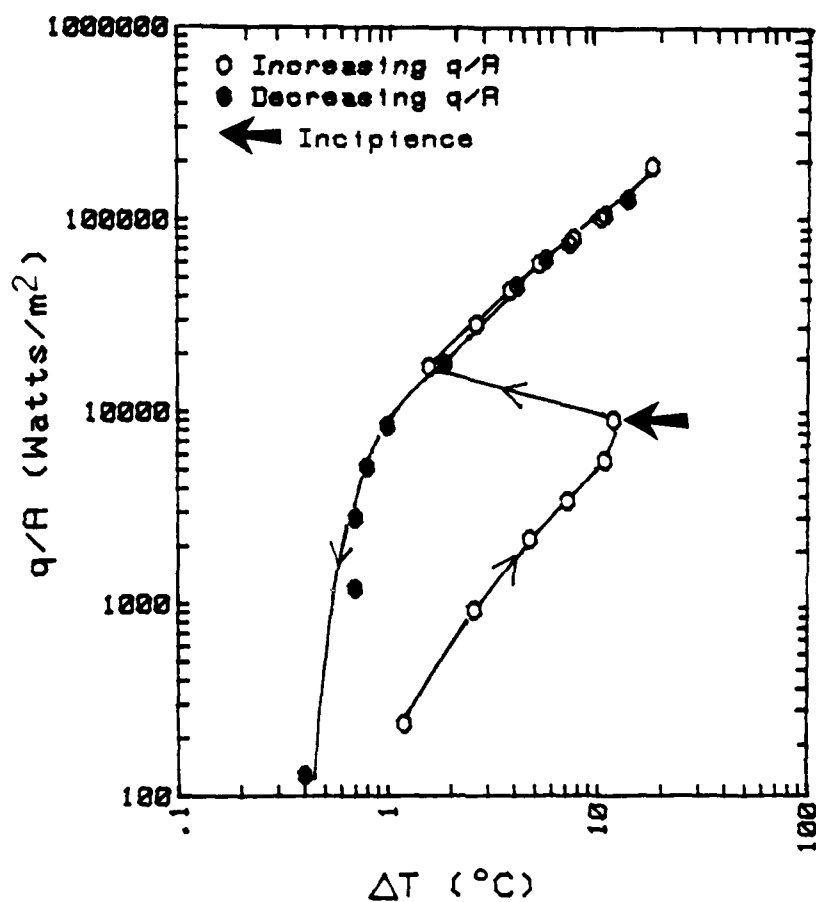


Figure 15. Thermoexcel-E Surface in R-113--Submerged in Pool Overnight

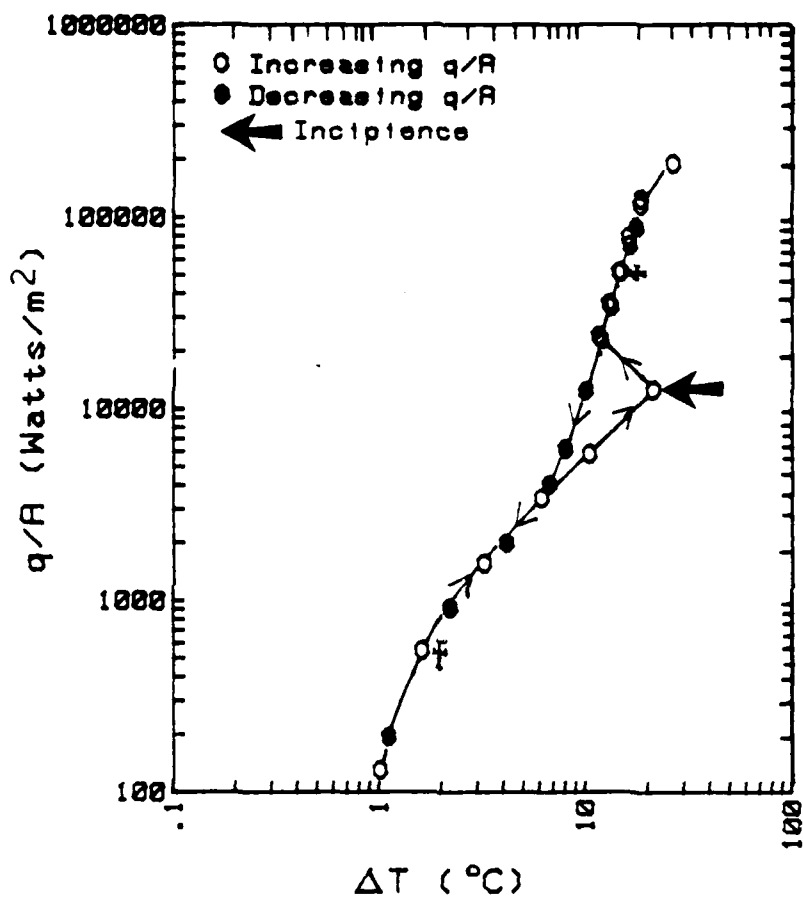


Figure 16. Plain Copper Tube in R-113--Submerged in Pool Overnight

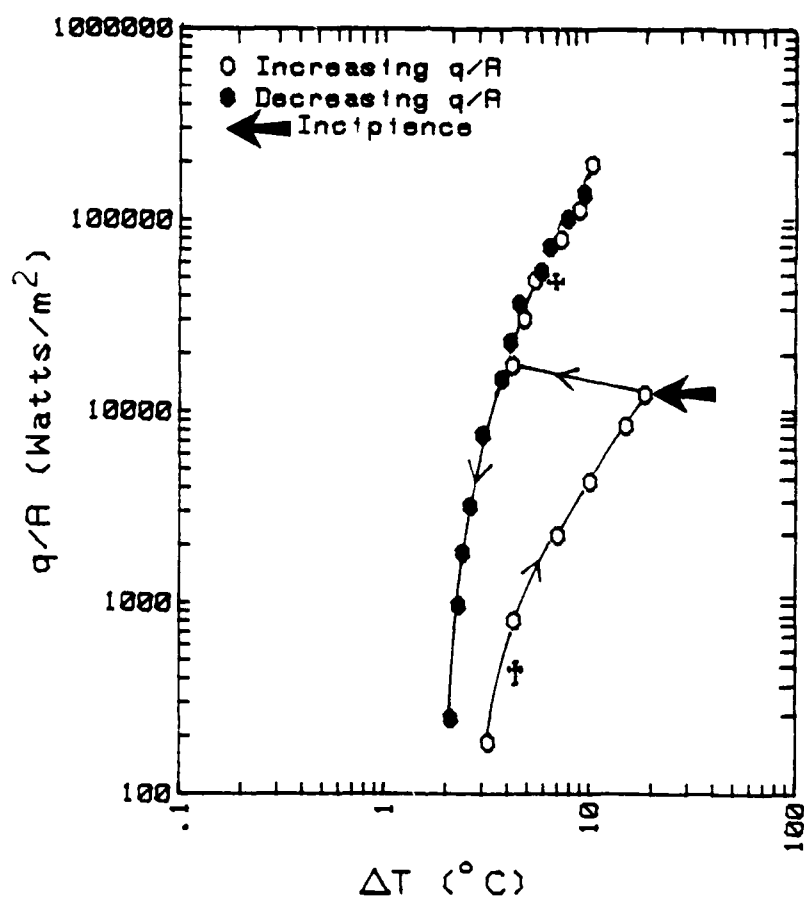


Figure 17. Gewa-T Surface in R-113--Submerged in Pool Overnight

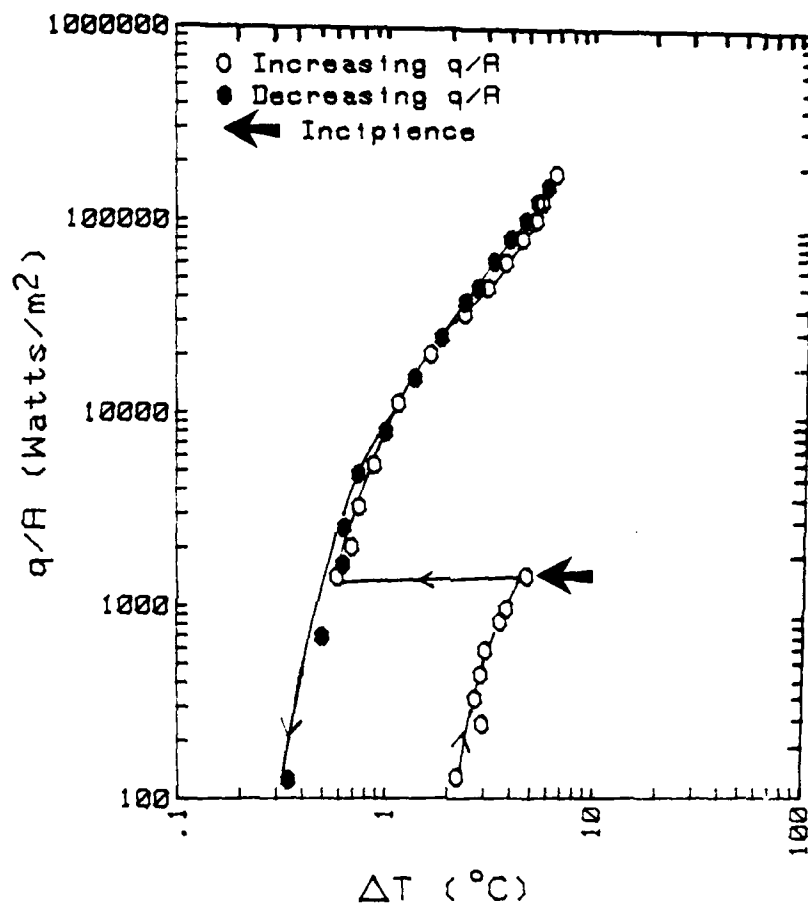


Figure 18. High Flux Surface in R-113--Aged at 30,000 W/m<sup>2</sup> for One Hour then Cooled for 30 Minutes

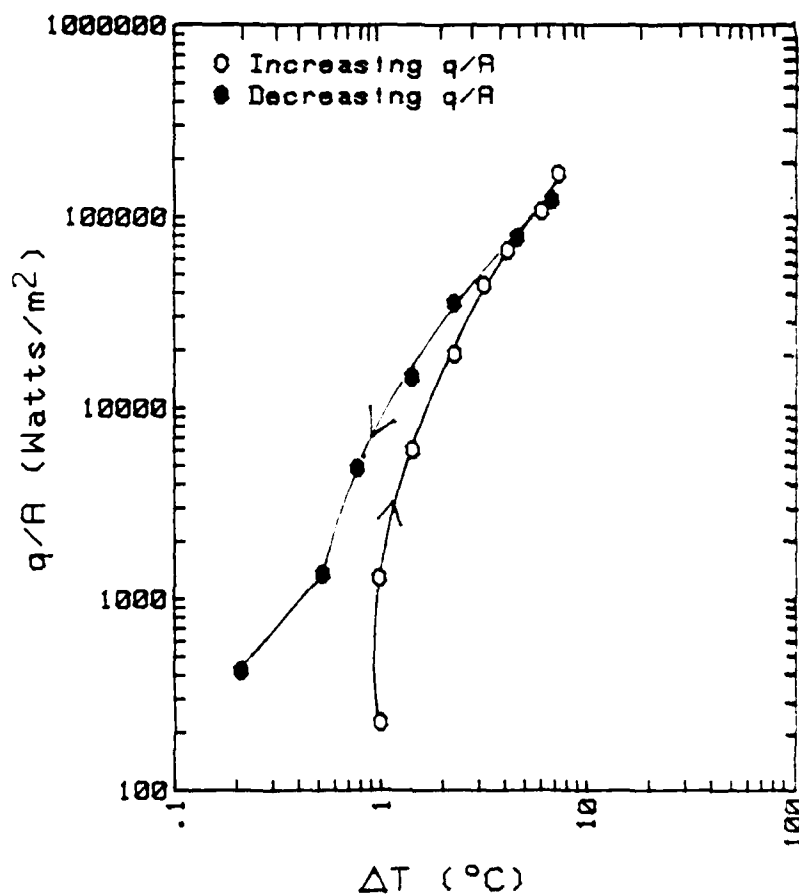


Figure 19. High Flux Surface in R-113--Aged at 30,000 W/m<sup>2</sup> for One Hour

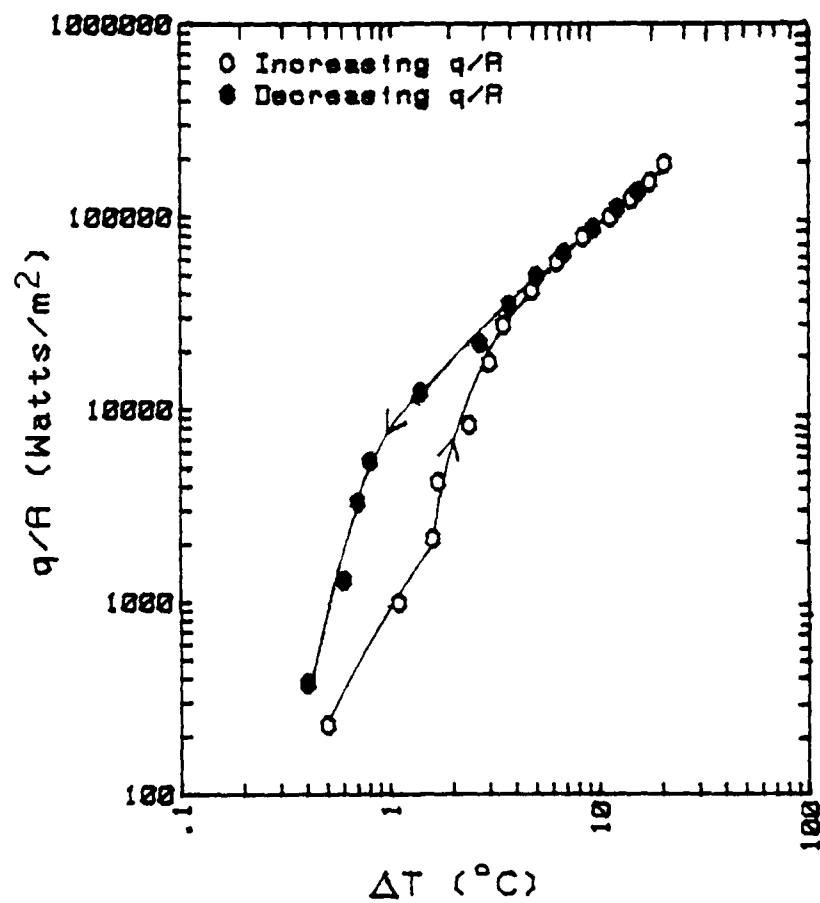


Figure 20. Thermoexcel-E Surface in R-113--Aged at 30,000 W/m<sup>2</sup> for One Hour

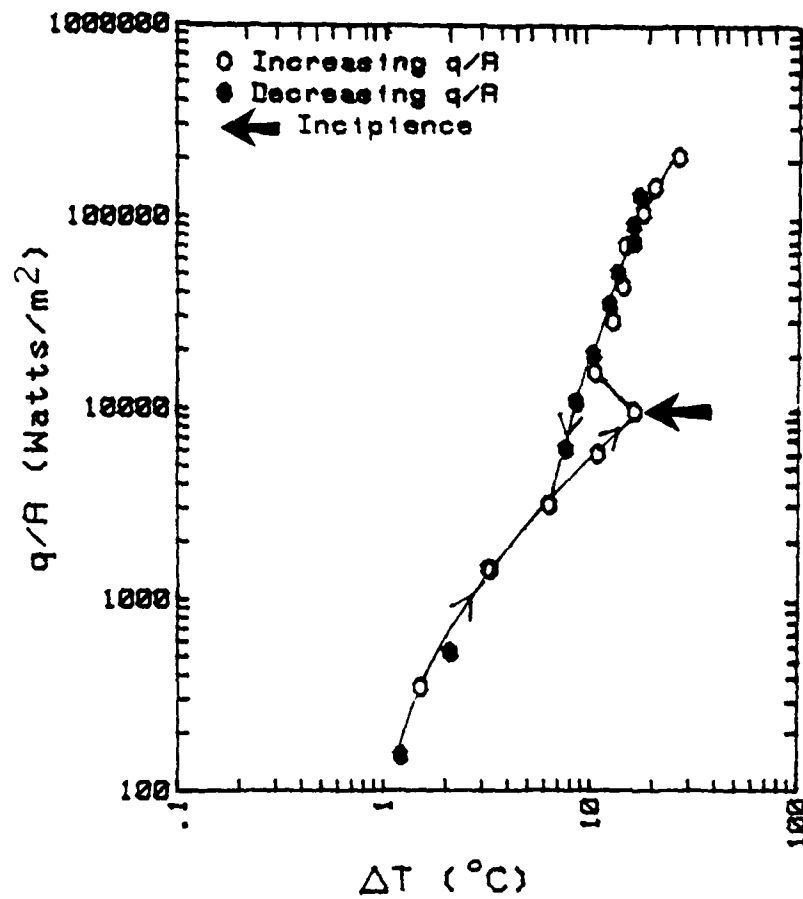


Figure 21. Plain Copper Tube in R-113--Aged at 30,000 W/m $^2$  for One Hour



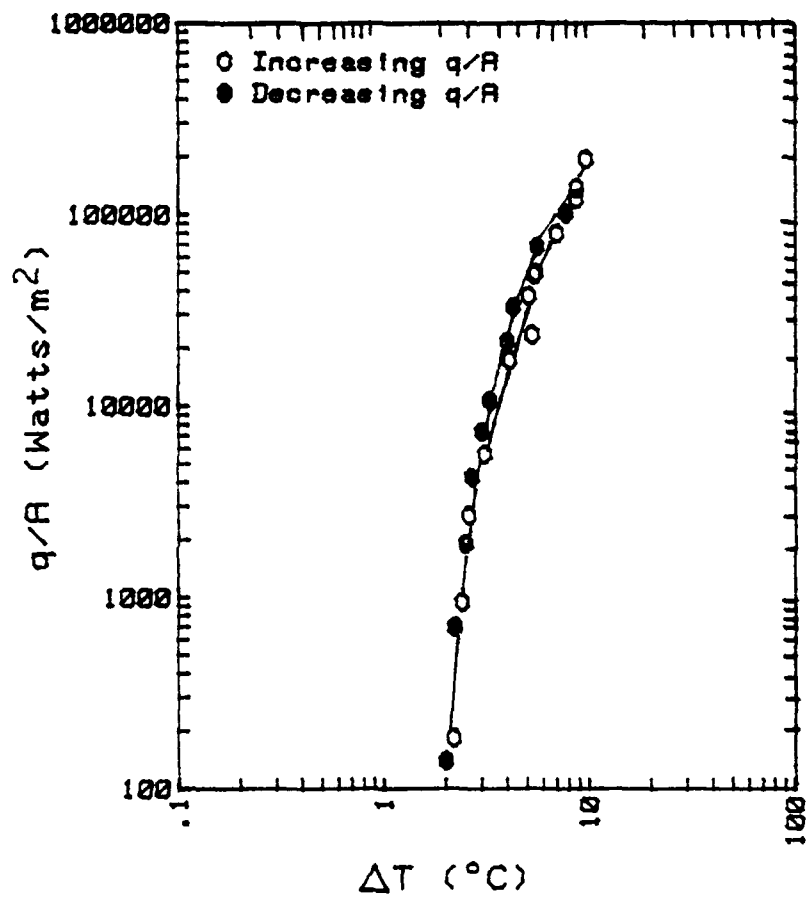


Figure 22. Gewa-T Surface in R-113--Aged at 30,000 W/m<sup>2</sup> for One Hour

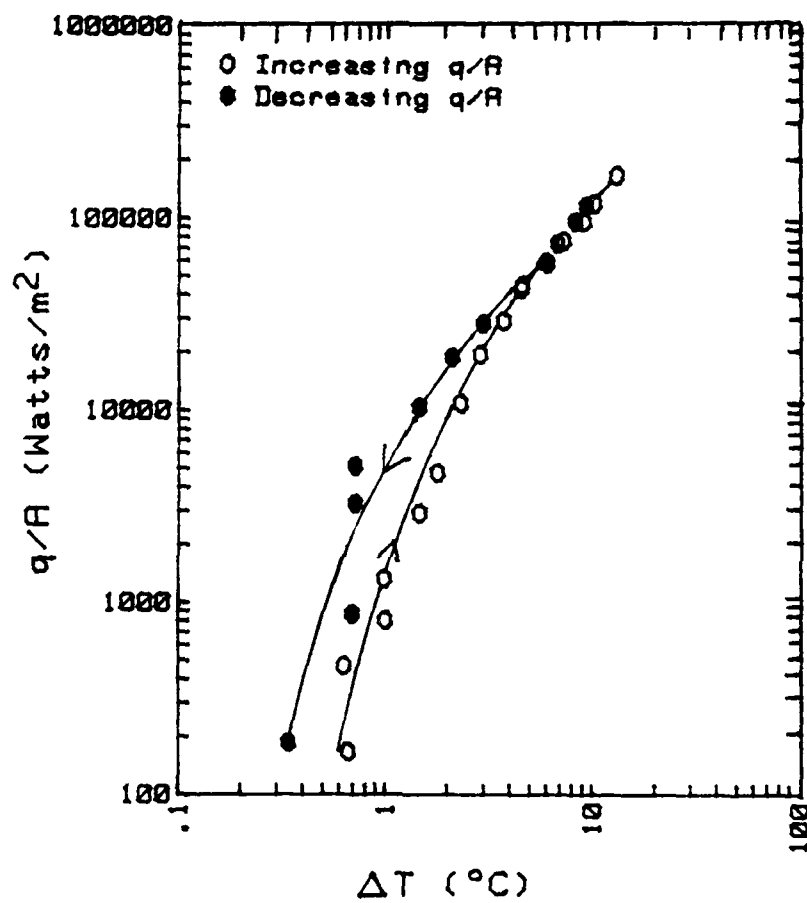


Figure 23. High Flux Surface in R-113--Air  
Dried at 65°C for Ten Minutes

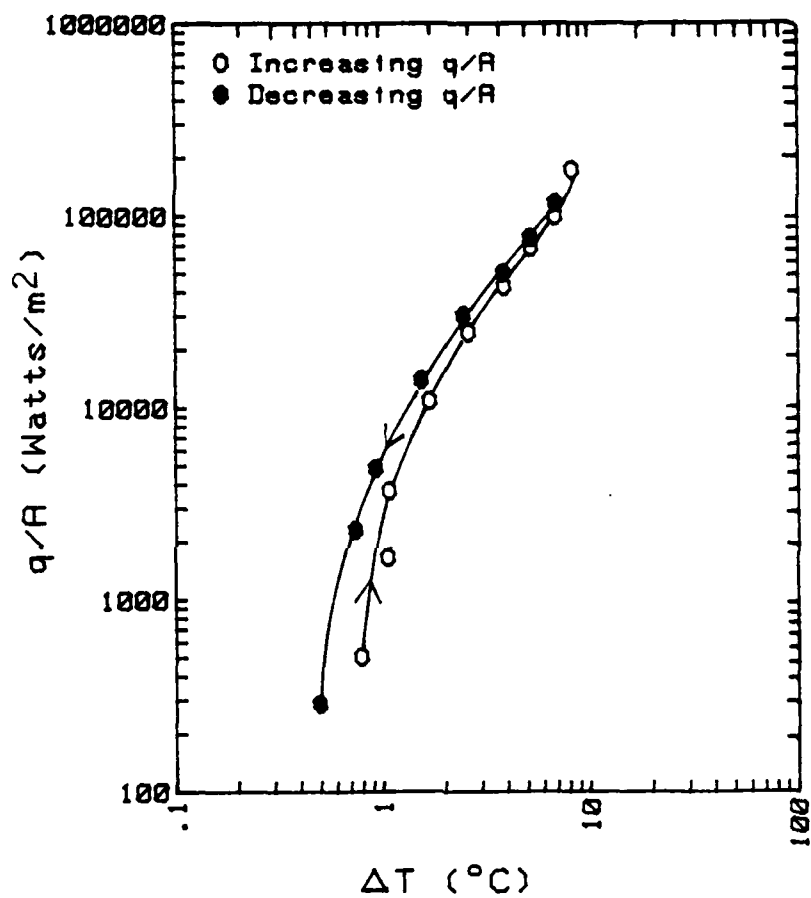


Figure 24. High Flux Surface in R-113--Air  
Dried at 65°C for Ten Minutes

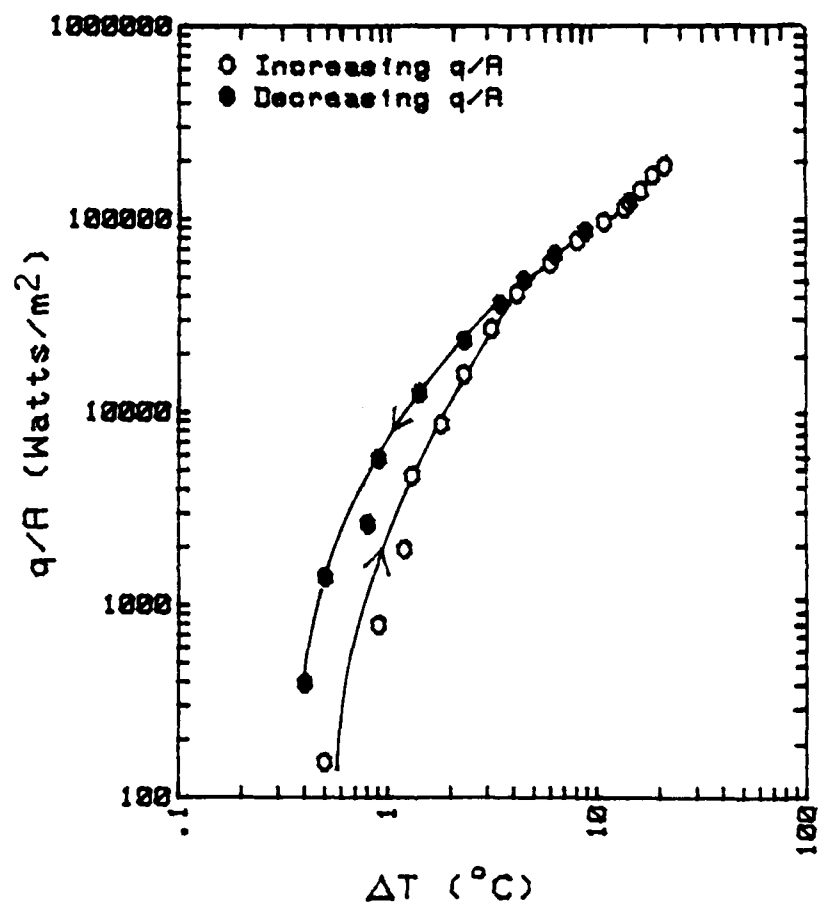


Figure 25. Thermoexcel-E Surface in R-113--Air  
Dried at 65°C for Ten Minutes

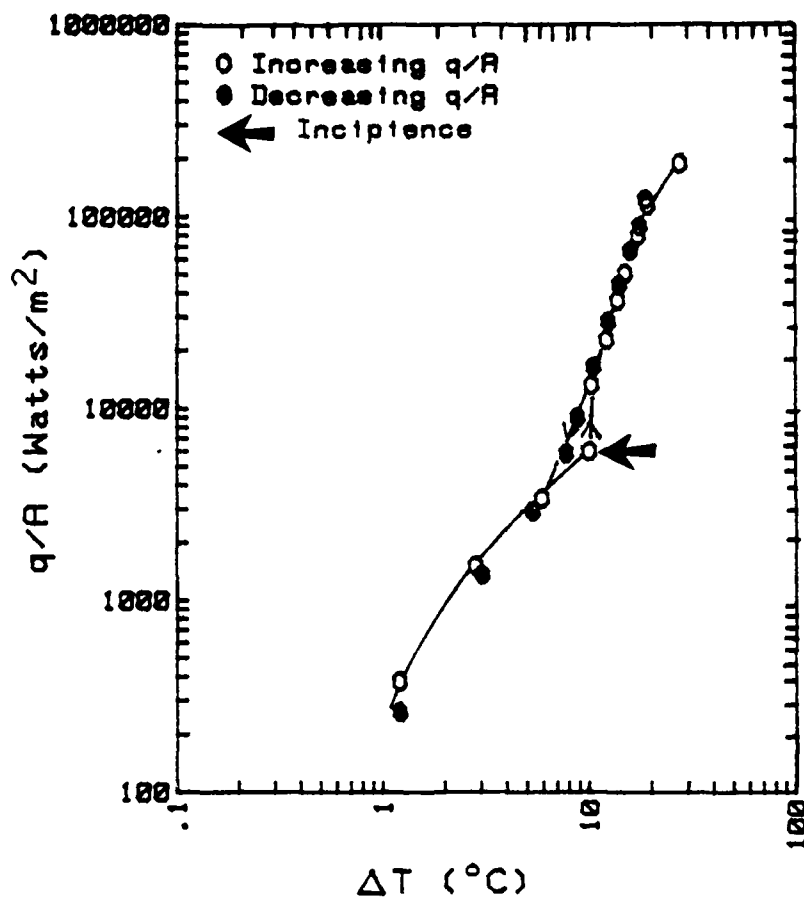


Figure 26. Plain Copper Tube in R-113--Air  
Dried at 65°C for Ten Minutes

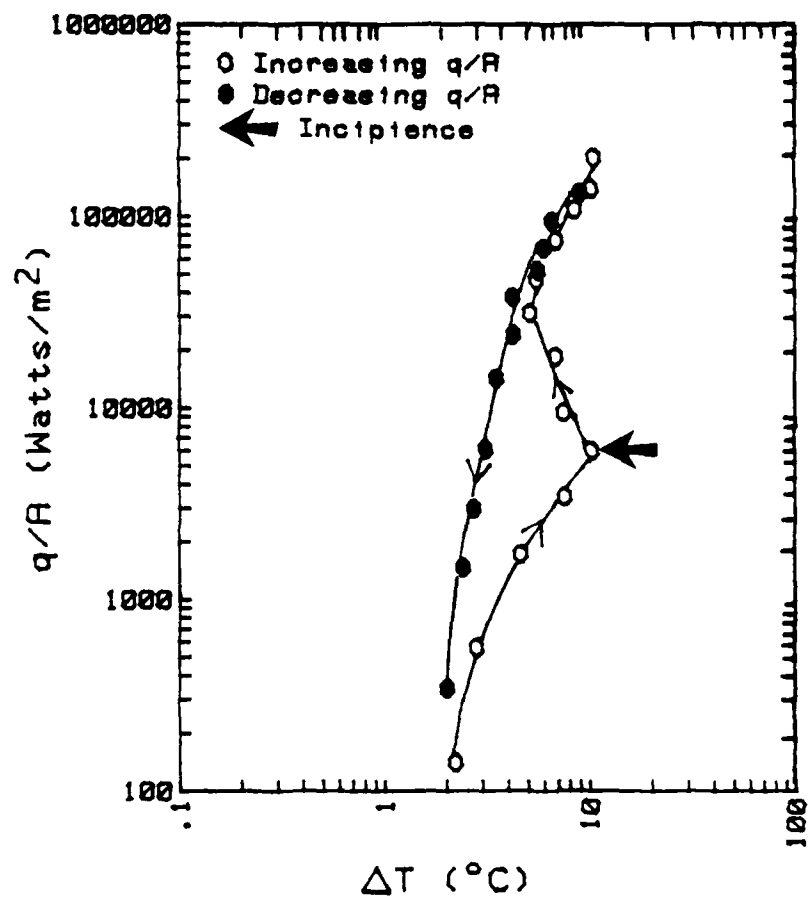


Figure 27. Gewa-T Surface in R-113--Air  
Dried at 65°C for Ten Minutes

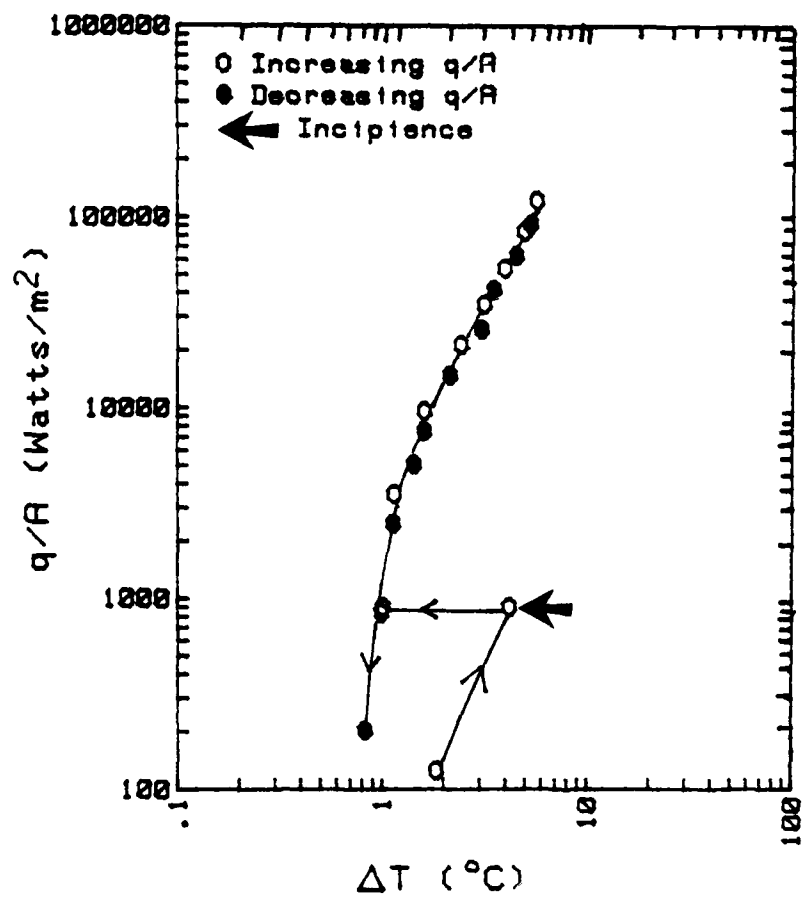


Figure 28. High Flux Surface in FC-72--Submerged in Pool Overnight

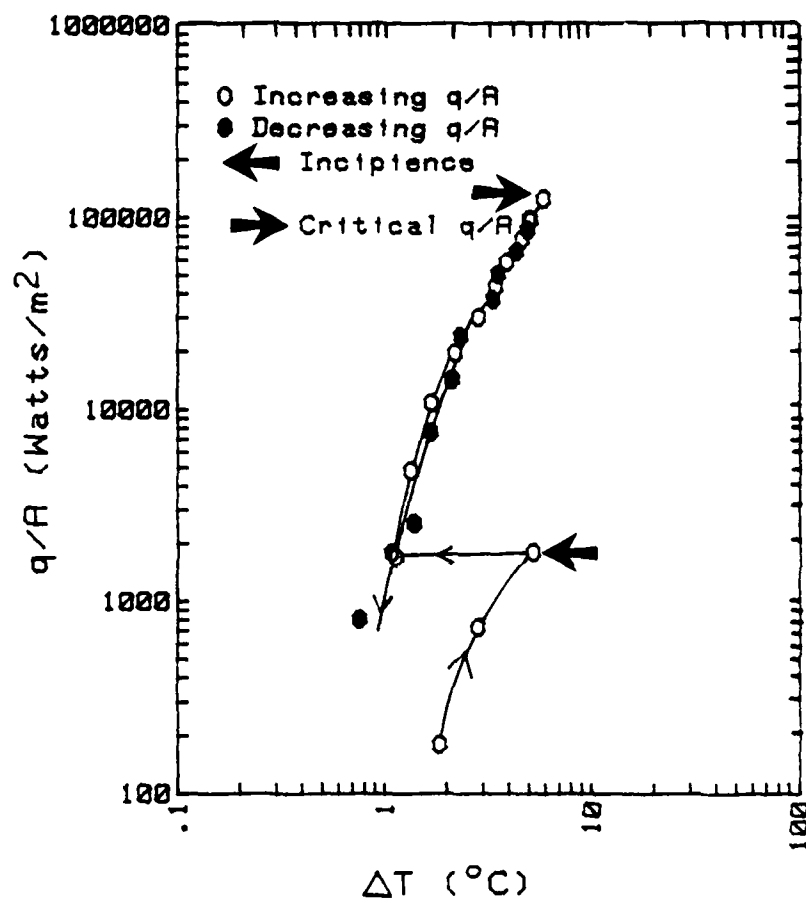


Figure 29. High Flux Surface in FC-72--Submerged in Pool Overnight



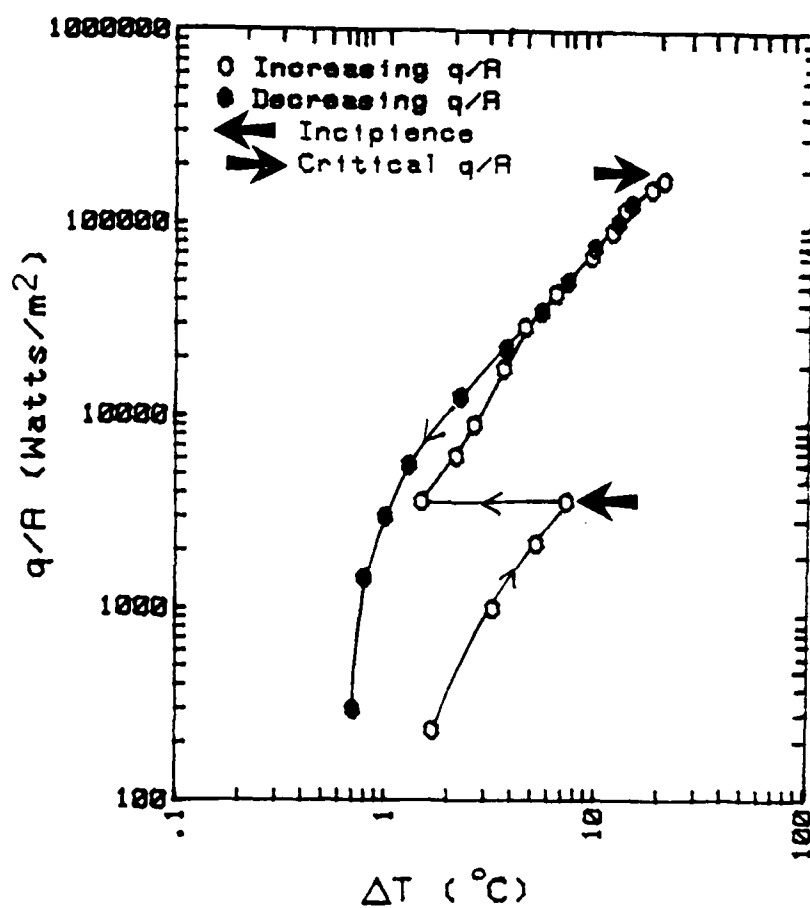


Figure 30. Thermoexcel-E Surface in FC-72--  
Submerged in Pool Overnight

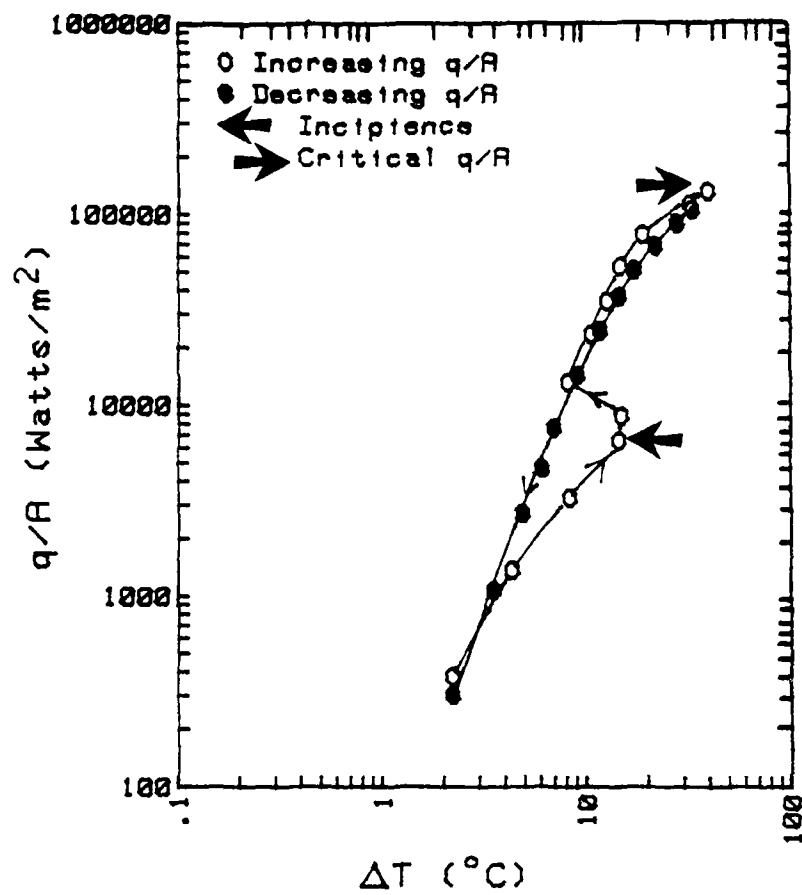


Figure 31. Plain Copper Tube in FC-72--  
Submerged in Pool Overnight

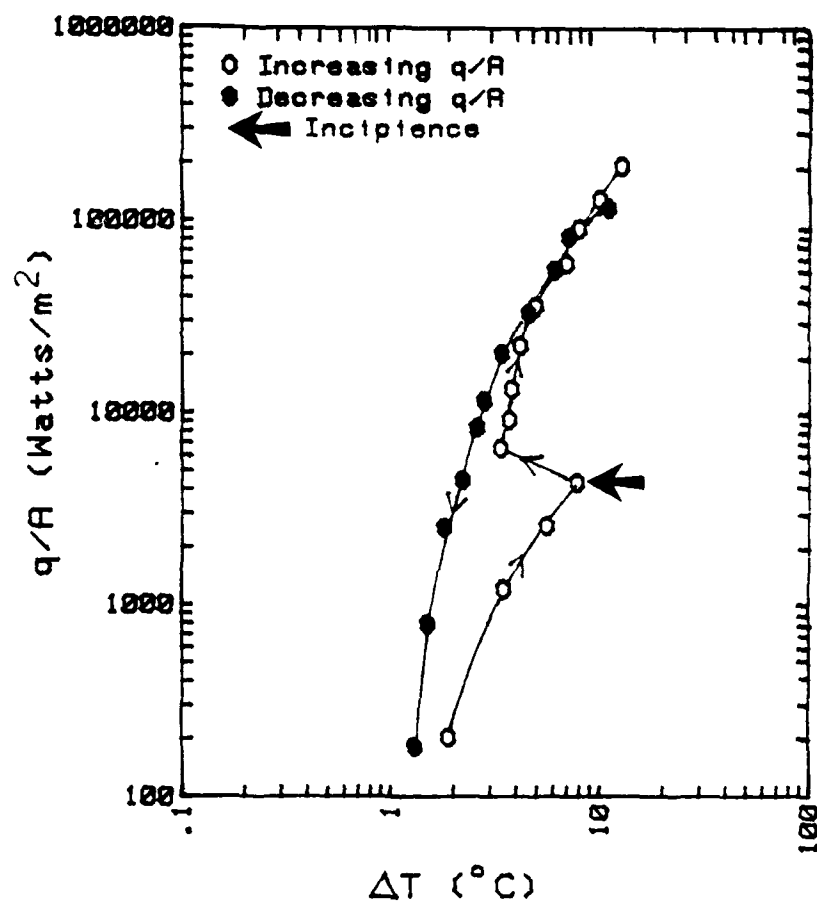


Figure 32. Gewa-T Surface in FC-72--  
 Submerged in Pool Overnight

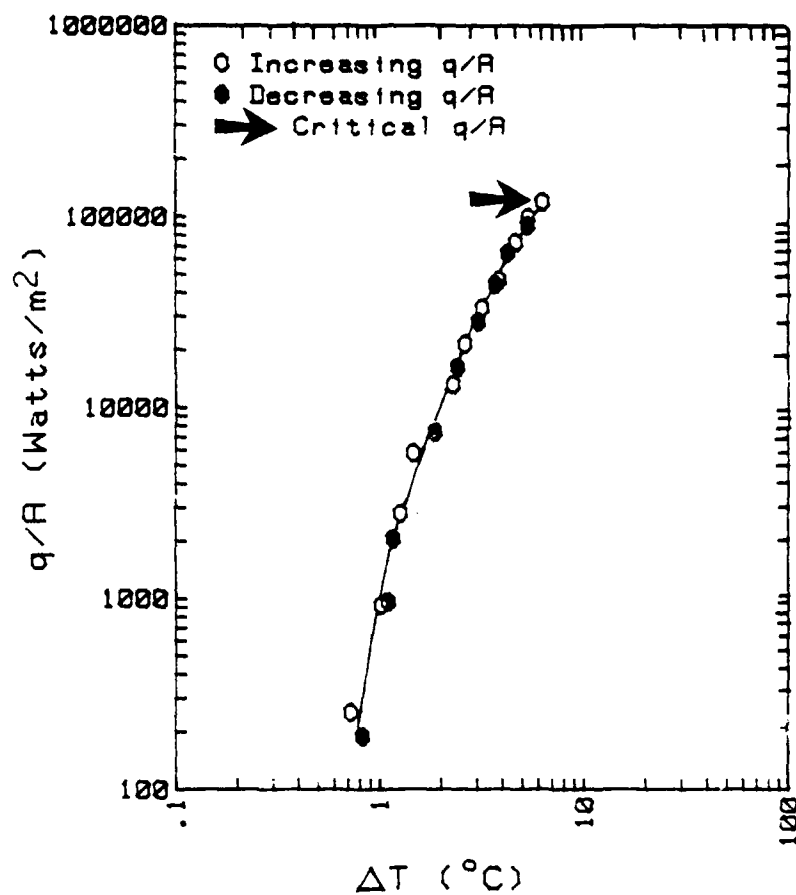


Figure 33. High Flux Surface in FC-72--Aged at 30,000 W/m<sup>2</sup> for One Hour

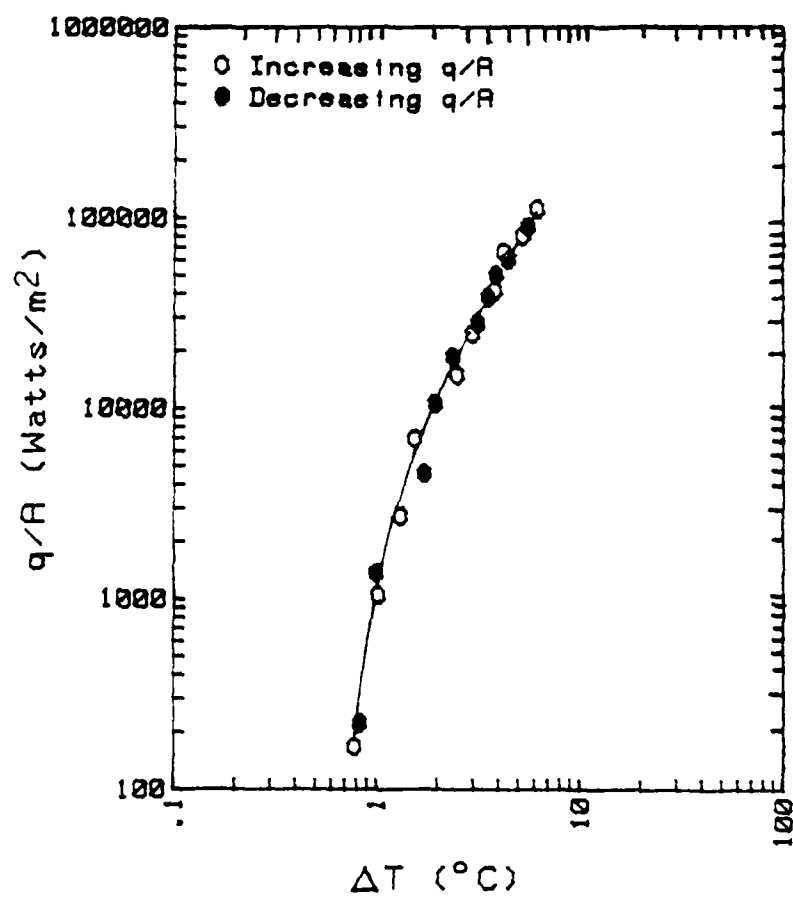


Figure 34. High Flux Surface in FC-72--Aged  
at 30,000 W/m<sup>2</sup> for One Hour

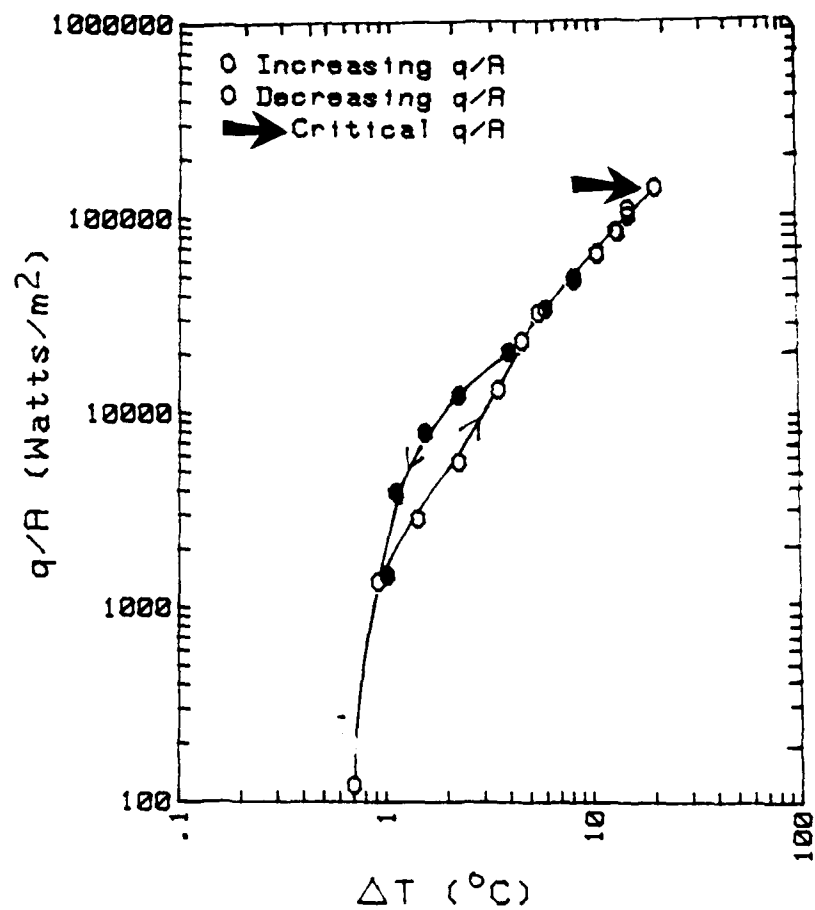


Figure 35. Thermoexcel-E Surface in FC-72--Aged at 30,000 W/m<sup>2</sup> for One Hour

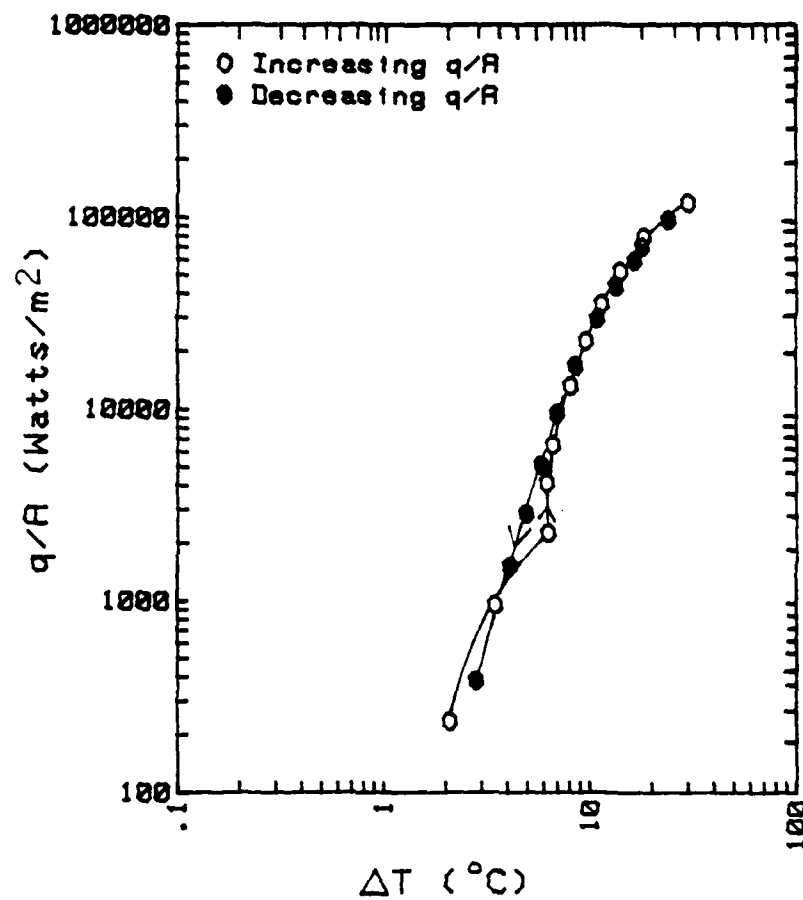


Figure 36. Plain Copper Tube in FC-72--Aged at 30,000 W/m<sup>2</sup> for One Hour

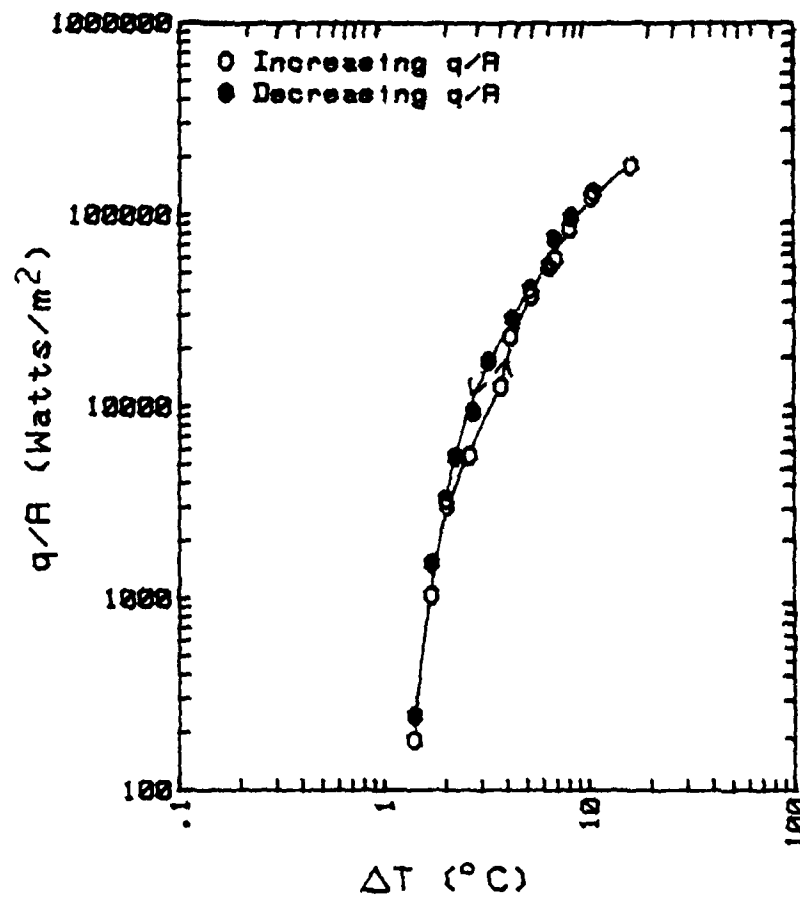


Figure 37. Gewa-T Surface in FC-72--Aged at 30,000 W/ $m^2$  for One Hour



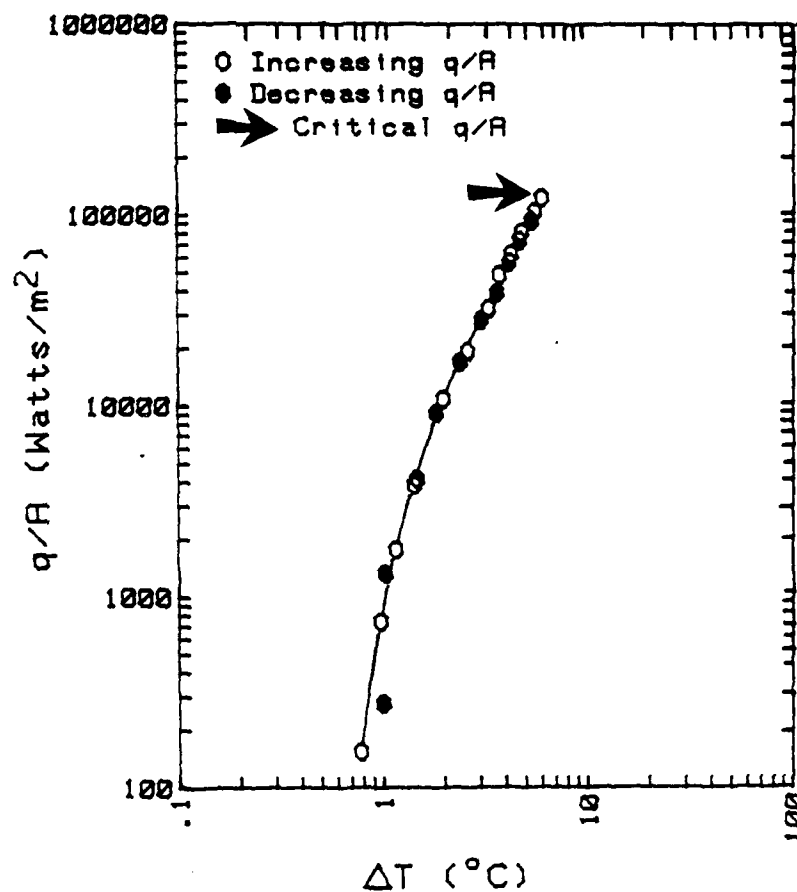


Figure 38. High Flux Surface in FC-72--Air  
Dried at 65°C for Ten Minutes

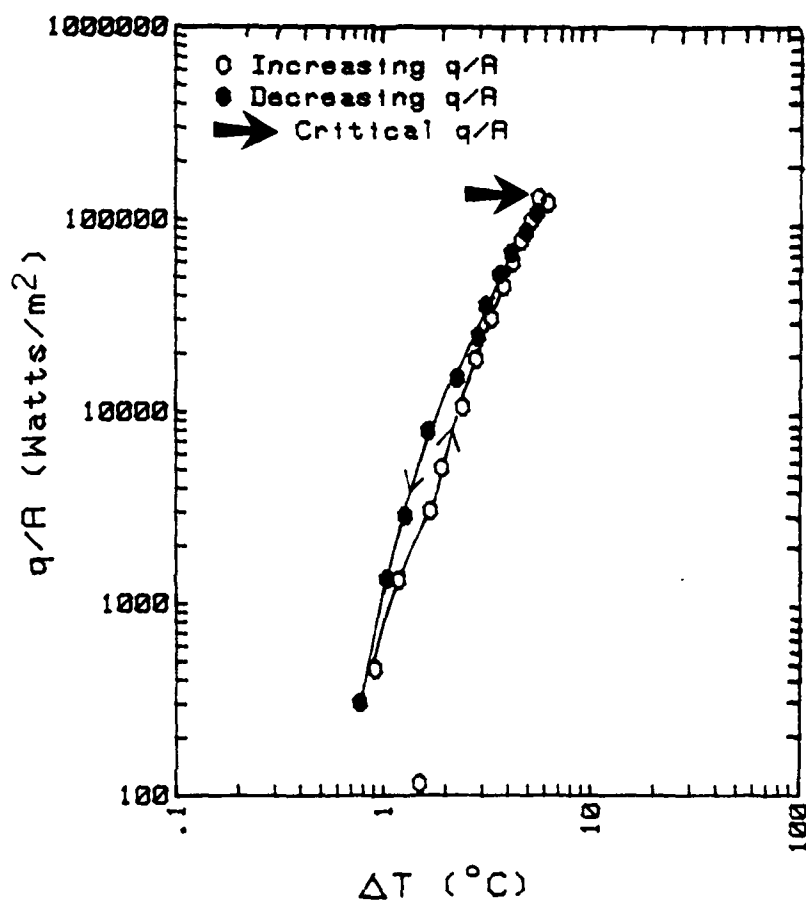


Figure 39. High Flux Surface in FC-72--Air  
Dried at  $65^{\circ}\text{C}$  for Ten Minutes

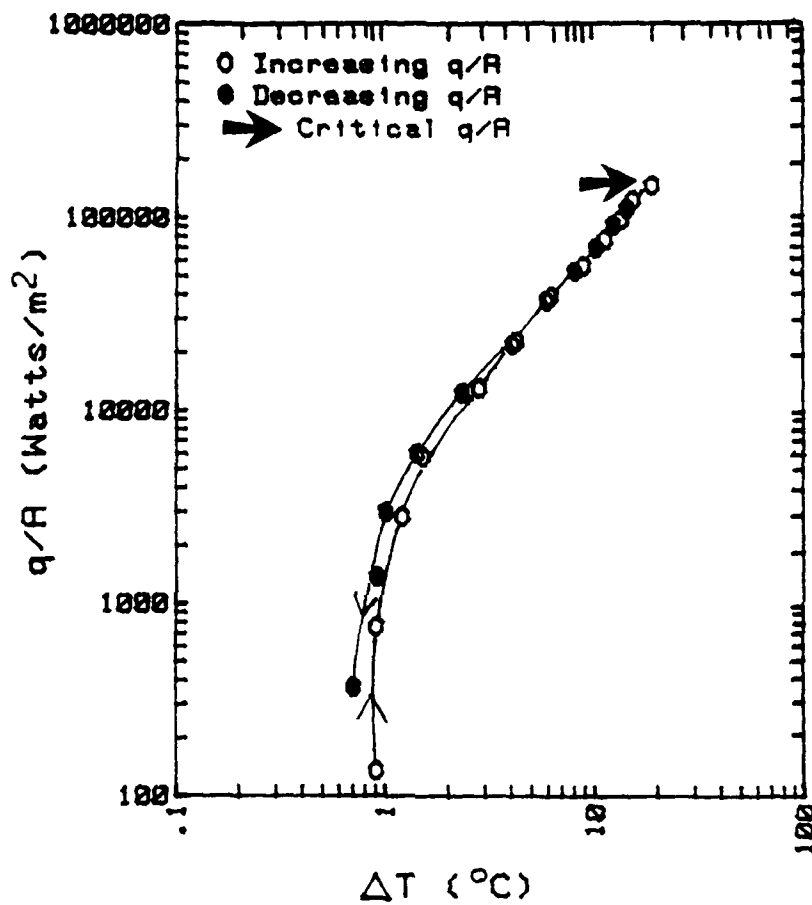


Figure 40. Thermoexcel-E Surface in FC-72--Air Dried at 65°C for Ten Minutes

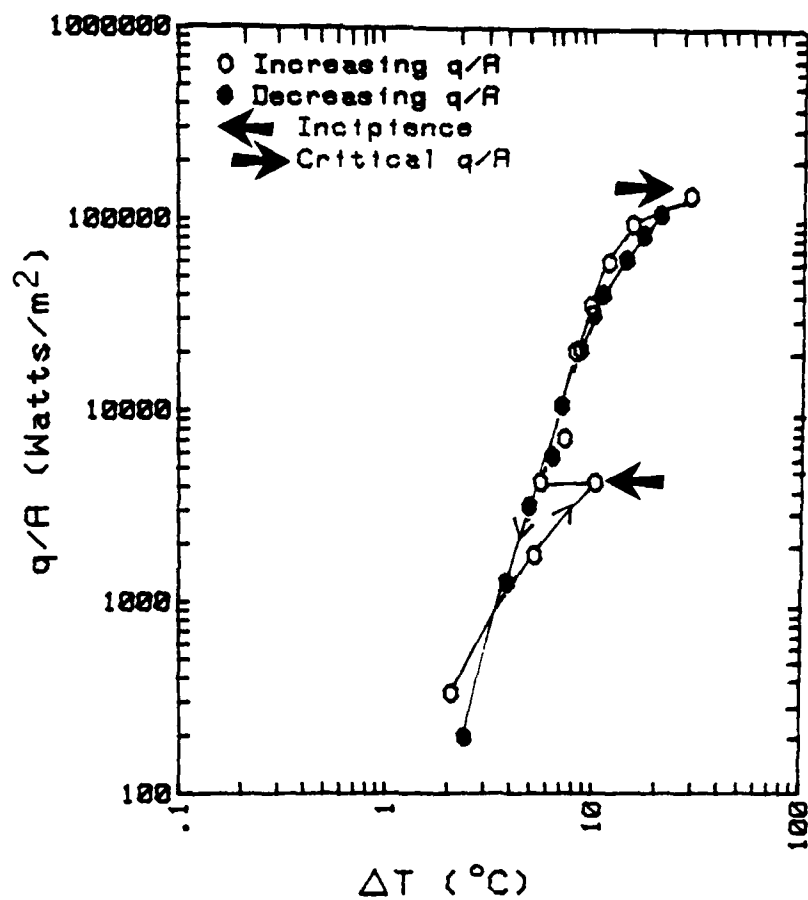


Figure 41. Plain Copper Tube in FC-72--Air  
Dried at 65°C for Ten Minutes

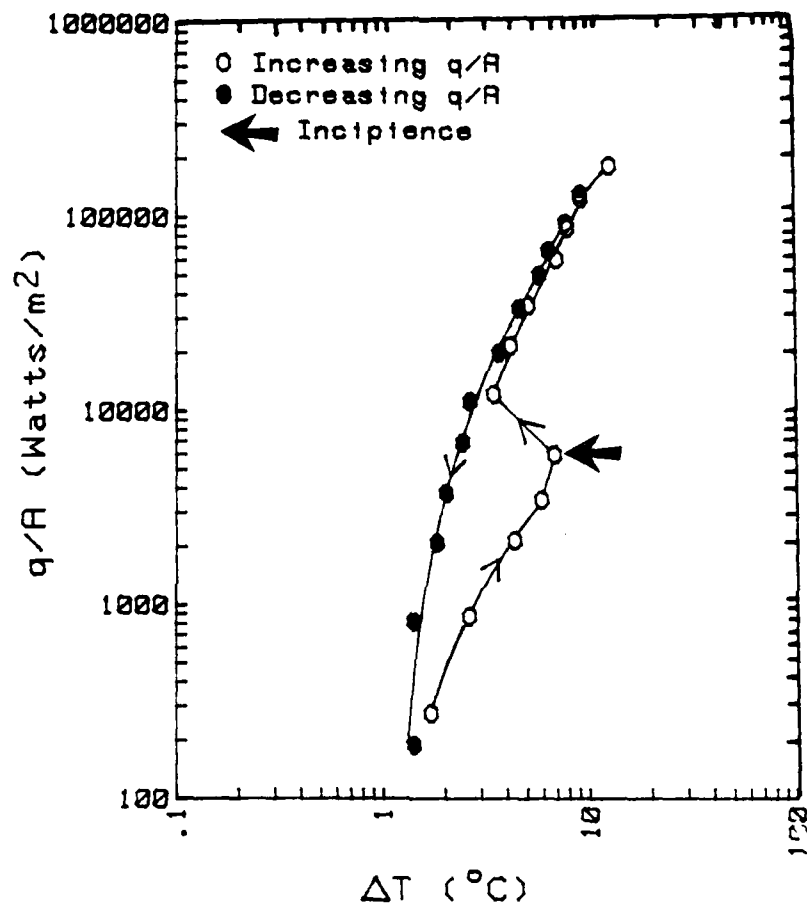


Figure 42. Gewa-T Surface in FC-72--Air  
Dried at 65°C for Ten Minutes

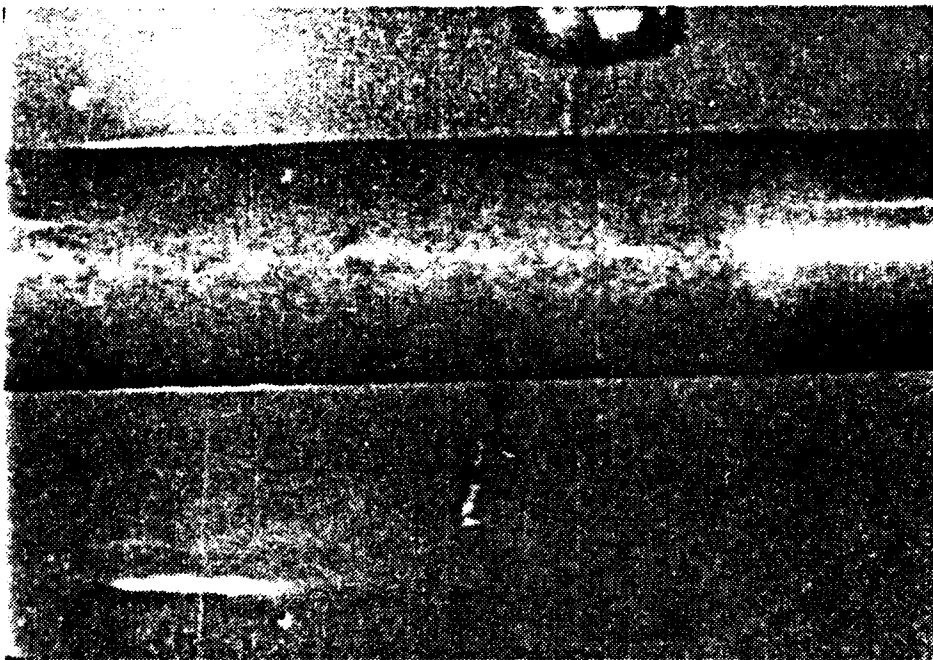


Figure 43. High Flux Surface in R-113 Prior to Boiling Initiation

Figures 43-46 Movie sequence at 64 frames/sec of the High Flux surface in R-113 during the initiation of boiling, after being submerged in the liquid pool overnight

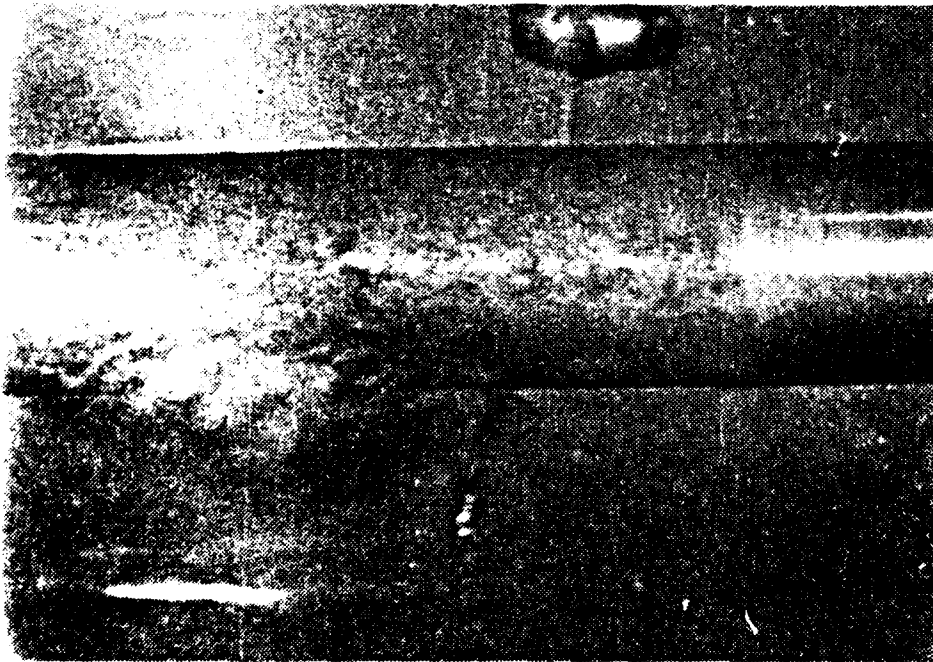


Figure 44. High Flux Surface in R-113 at  
Incipient Point



Figure 45. Activation of Entire High Flux Surface  
after Boiling Initiation



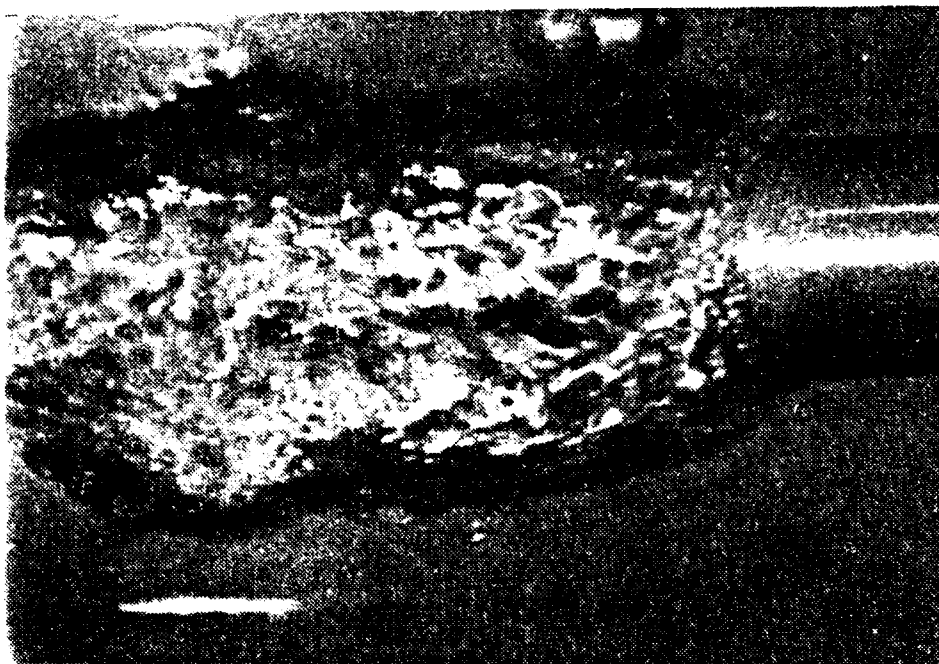


Figure 46. High Flux Surface in R-113 with  
Nucleate Boiling Established

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NUCLEATE POOL BOILING OF HIGH DIELECTRIC FLUIDS FROM ENHANCED S--ETC(U)

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